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ABSTRACT

The report details the development and design of a mechanical hand for communicating with deaf blind persons. It is explained that the device, which looks and functions like the human hand, forms the symbols of the one-hand manual alphabet upon command from a standard electric typewriter keyboard. The report addresses the following topics (sample subtopics in parentheses): background of the concept (prior work by the Southwest Research Institute, including the use of surgically implanted electrodes); design criteria (mechanical hand dimensions, detailed drawings of the finger and thumb designs); the development program; consultant reactions; and needed improvements (cosmesis, internal resistance, and portability). Among six recommendations listed are for a functional design evalution by deaf blind users, attention to cosmetology, and preparation of a final report to determine disposition. (CL)

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Final Report

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Grant No.: G-0076-05771

FURTHER DEVELOPMENT AND TEST OF AN ARTIFICIAL HAND FOR COMMUNICATION WITH DEAF-BLIND PEOPLE

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ABSTRACT

This report discusses the design and fabrication of a mechanical hand for communicating with deaf-blind individuals. The mechanical hand, which looks and functions much like the human hand, forms the symbols of the one-hand manual alphabet upon command from a standard electric typewriter keyboard.

A fully-articulated mechanical hand was designed and fabricated. The device has a life-like appearance and performance even though it does not yet have a suitable cosmetic covering. It can form acceptable symbols for much of the one-hand manual alphabet at a speed approaching a conversational rate. Programming changes, with collaboration of deaf-blind participants, will improve presentation of certain letters. It is felt that the mechanical hand still retains promise as a communication and a training aid for deaf-blind people.

Covered in the report are discussions of the background of the concept, design criteria, the development program, and a description of the mechanical hand built during this project. The device has had minimum usage by deaf-blind people. However, comments regarding its functionality and changes and improvements are presented. A proposed evaluation program for the hand using deaf-blind consultants is also outlined.

ACKNOWLEDGMENTS

The success of this project was due to the contributions of many people.

The consultants; Dr. Fred Kruger and the staff of the National Center for Deaf-Blind Youths and Adults; Jacqueline Lloyd and Rod Granbury of San Antonio College; and Vinnie Cecil of the Southwest Center for the Hearing Impaired.

The Southwest Research Institute engineers and technicians: Sam McFarland, Billy Carpenter, Menan Hanz, Gerry Driscoll, and Hal King.

The reason: Richard Bell and the other deaf-blind friends who have provided the encouragement, criticisms and suggestions that have made the improved prototype mechanical hand for communication with deaf-blind people a reality.

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I. INTRODUCTION

A. Summary

This report discusses the design and fabrication of a mechanical hand for communicating with deaf-blind individuals. The mechanical hand, which looks and functions much like the human hand, forms the symbols of the one-hand manual alphabet upon command from a standard electric typewriter keyboard.

Covered in the report are discussions of the background of the concept, design criteria, the development program, and a description of the mechanical hand built during this project. The device has had minimum usage by deaf-blind people; however, comments regarding its functionality and changes and improvements are presented. A proposed evaluation program for the hand using deaf-blind consultants is also outlined.

B. Background

Almost all communication with deaf-blind people is of the "hands-on" type; that is, we must physically touch them in some way. We must (1) "write" in their hands, (2) use the one-hand manual alphabet in which case they embrace our hand (see Fig. 1), or (3) permit them to put their hands on our lips, jawbone, and throat to "lip" read (the Tadoma method). The equivalent of "talking books" used by the blind does not exist for these people. Since they have so little opportunity to communicate, many of them are functionally retarded. It is difficult to take the census of this segment of society so the number is not accurately known; a substantial increase in the number of deaf-blind people is expected because of the rubella epidemic that occurred several years ago.

There have been numerous efforts to develop tactile, vibrotactile, and electrotactile communication methods for people who are both deaf and blind. The National Center for Deaf-Blind Youths and Adults (NCDBYA) is cognizant of existing and proposed methods and is presently engaged in a field test of their Telebraille and development of their "Wrist Com" system. Even so, they recognize the need for improved methods and systems; and they encourage the scientific community to conceive more efficacious and potentially economical approaches.

About thirty engineers, psychologists, and specialists in neurological and communication rehabilitation were invited to a special meeting entitled "Workshop On Communication And Sensory Aids For The Deaf Blind" at NCDBYA in November of 1973.[1] The meeting was sponsored by the National Academy of Sciences. Its primary purpose was to elicit novel approaches for communication and sensory aids for multiply-impaired people.

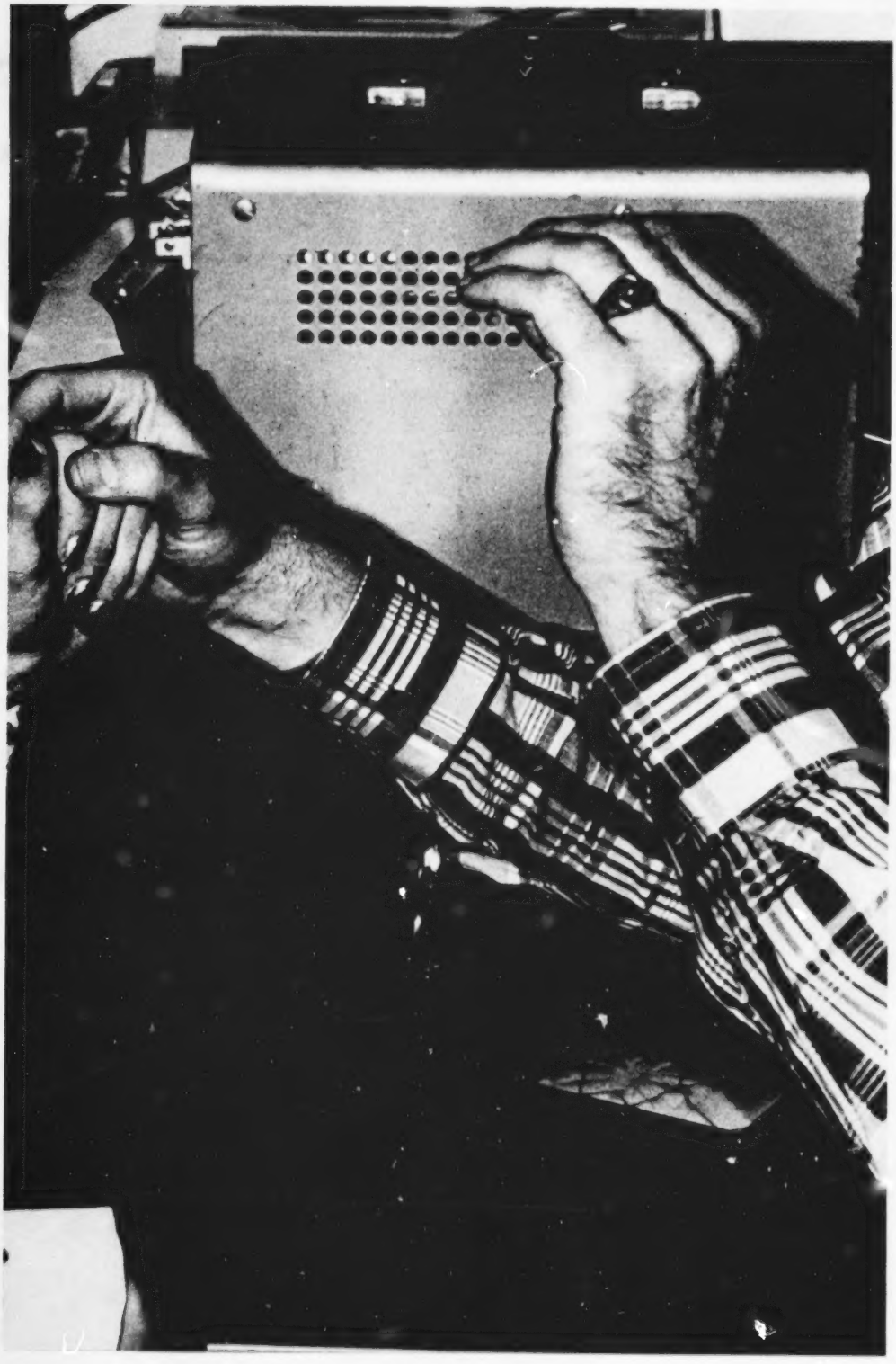

FIGURE 1. INTERPERSONAL COMMUNICATION
BY FINGER SPELLING

II. PRIOR WORK BY SOUTHWEST RESEARCH INSTITUTE

A. Approaches Conceived

Stimulated by the workshop, SwRI engineers conceived two approaches for developing communication methods for deaf-blind people. The first method involved surgical implantation of high-purity carbon electrodes, shown in Figure 2, to act as a stimulator array for coded input signals. The second method involved an electromechanical hand which "fingerspells" or makes the signs of the one-hand manual alphabet [2,3,4] as shown in Figure 3.

B. Electrotactile Method - Surgically Implanted Electrodes

The Internal Research Panel of Southwest Research Institute sponsored early investigation of implanted electrodes. In a program entitled "A New Communication Method for Deaf-Blind People," high purity carbon percutaneous electrodes were implanted in the arm of a SwRI staff member and tactual responses were observed at regular intervals for eight months. Although a reliable electrotactile stimulation method was demonstrated [5,6], clinicians and researchers discouraged further investigation because of the surgery involved. Research effort was then diverted to the communicating electromechanical hand.

C. Prototype Mechanical Hand Communicator

1. Summary

Under joint sponsorship by The Ewing Halsell Foundation* and the Internal Research Panel of SwRI, a feasibility demonstration prototype artificial hand, shown in Figure 4, was designed and fabricated. This work was reported in the Final Technical Report for SwRI Project 13-4035 dated 7 July 1975. The functional hand was demonstrated at the annual meeting of the Texas Rehabilitation Association in San Antonio and at a national training conference for therapists coordinated by the Texas Education Agency in Dallas in July 1975.

Two deaf-blind people, consultants and participants in this project, successfully identified letters presented by the artificial hand in the one-hand manual alphabet code. They indicated that they liked the hand and felt that they could learn to "copy" information presented at a conversational rate. Special educators and others engaged in teaching deaf-blind people also indicated that this approach appeared feasible.

2. Design Description

The original mechanical hand was composed of four fingers and a thumb mounted on an aluminum base plate. Each finger was controlled by

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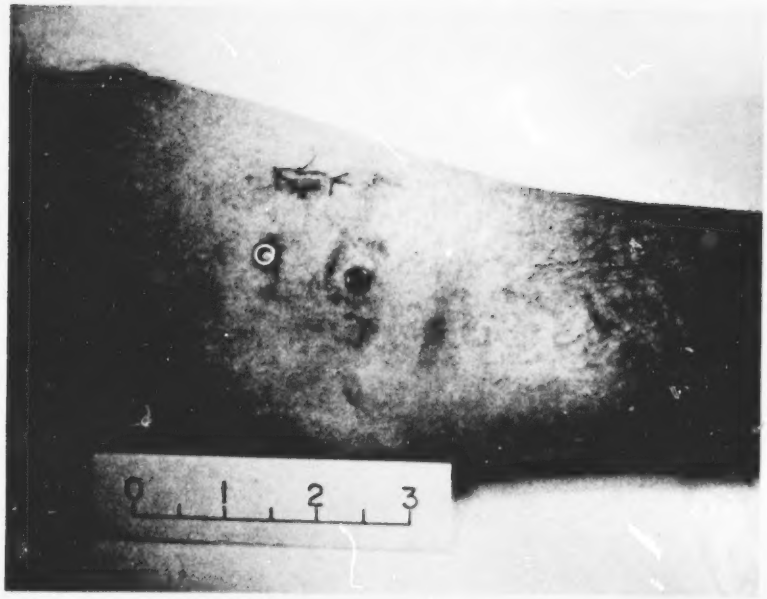


FIGURE 2a
SURGICALLY IMPLANTED
HIGH PURITY CARBON ELECTRODES
(IMPLANTED 19 OCTOBER 1973)

FIGURE 2b
REMOVAL OF CARBON ELECTRODES
LEFT MINOR SCARS
(REMOVED 14 JUNE 1974. ELECTRODES IN SITU 8 MONTHS)

FIGURE 2. HIGH PURITY CARBON ELECTRODES
FOR ELECTROSTIMULATION

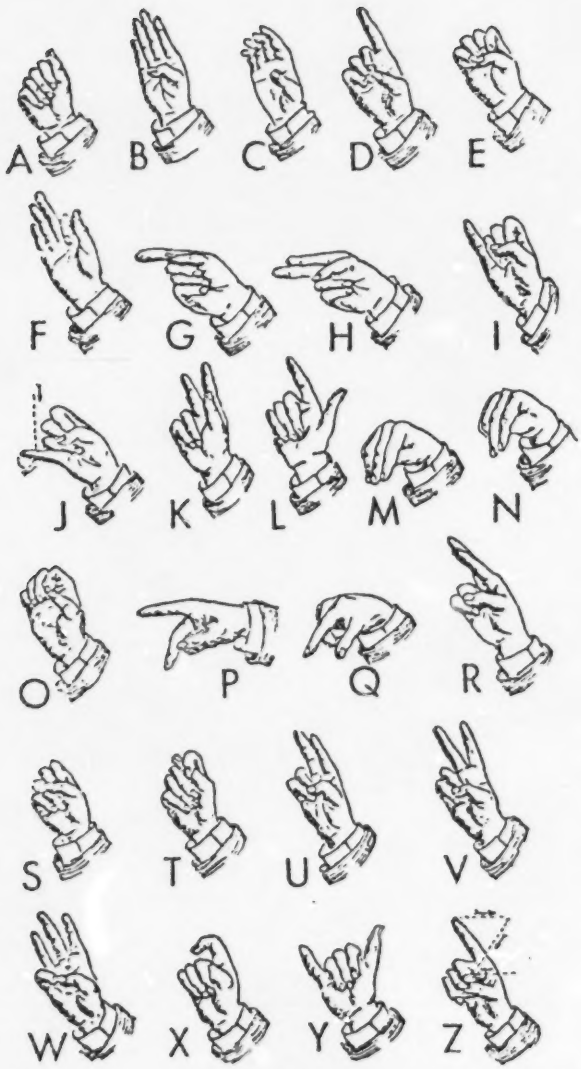


FIGURE 3. THE ONE-HAND MANUAL ALPHABET

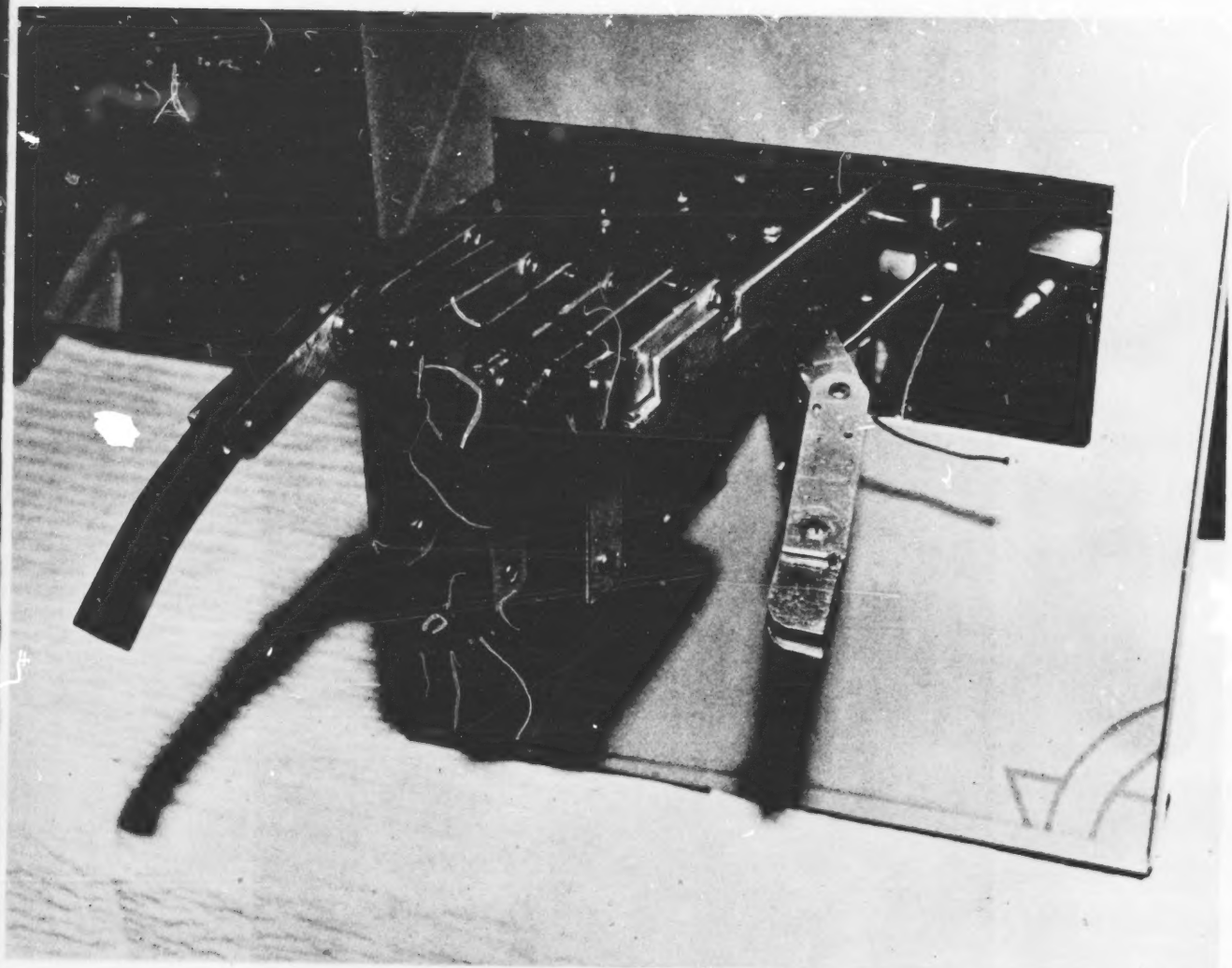


FIGURE 4. PROTOTYPE MECHANICAL HAND FOR DEAF-BLIND COMMUNICATION

two electrically driven solenoids, one to extend the finger and the other to flex the finger. The limits of travel were governed by stops at each joint. When the solenoids were de-energized, adjustable compression springs returned the fingers to a half-flexed position similar to that of a physiologic hand.

The fingers were composed of two segments, a carpophalangeal end segment and a phalangeal segment. This differs from the physiologic finger which has three segments. The decision to combine the last two segments into a rigid member was made after analysis of the one-hand alphabet showed there was little relative motion between these segments when forming letters. The carpophalangeal segment on all four fingers had a 10-degree angle between the pseudocarpal segment and its mating phalange.

It was also noted during analysis of the one-hand alphabet that the angle between the carpophalangeal end-segment and phalange was approximately equal to the angle between the phalange and the palm for all hand positions. Based upon this, the fingers were designed such that the carpophalangeal segment was controlled by a cross-belt pulley arrangement. This simplified the design and provided a reasonably lifelike behavior of the fingers.

A finger-spreading action was provided in the original hand for the letters V and W . This was provided by designing the index finger and ring finger mount to allow the finger to rotate. Springs normally held these mounts against stops so that the fingers were straight. To spread the fingers, the mounts were rotated by a single solenoid acting through a cable yoke.

The thumb was quite similar in design and action to the fingers except that three segments were used. The end-segment was controlled by the same pulley arrangement as the fingers. The thumb was extended away from the hand in a "hitch-hiker" attitude. The initial solenoid pull rotated the thumb toward the palm and fingers until the two end segments were parallel to the fingers. The second pull then rotated the end segments under the fingers for full flexion.

Inclination of the thumb away from the palm was accomplished by a hinged mount for the thumb. At rest, the thumb was held close to the palm by a spring. When abduction was desired, a solenoid pulled down on the thumb mount to incline the thumb away from the palm.

In the prototype hand, the twelve solenoids needed to power and control the fingers and thumb were mounted to the same structure as the fingers. The solenoids were mounted vertically and the draw strings routed to them by rollers to minimize hand size. The hand was supported over its center of mass by a gymbal. The gymbal provided the mobility needed to simulate wrist flexion and ulnar (outward) deviation which is used for several of the signs. Downward flexure and side rotation were produced by solenoids and return springs. The prototype hand had approximately 10° downward

extension and about 30° deviation to the right (ulnar). Some disadvantages were noted by the designers. Since the drive solenoids moved as the hand moved, the wrist motion was very slow; and large vibrations were produced when the heavy solenoid assembly was stopped. No provisions were made to allow programming changes to alter mechanical responses of the hand for proper sign formation.

The artificial hand was packaged in an 8" x 10" x 12" cabinet. It also housed the power supply and control circuitry for the solenoids. A separate electronic unit contained a standard electric typewriter keyboard and the electronic circuitry that converted the electric typewriter code to the one-hand manual alphabet code.

3. Test Results and Evaluation

In controlled experiments using the original hand, two deaf-blind consultants identified the letters B, C, F, I, J, V, W, and Z with 100% accuracy. Their accuracy in identifying the letters G, H, M, and U was better than 70%. Five letters of the alphabet, D, K, O, R, and T, as programmed into the system, were totally unrecognizable by the consultants. In the case of the letters O, R, and T, gross approximations or alternate signs had been programmed to simplify the hand design. After the hand was built, it was found that producing a more accurate approximation of these signs would have been less difficult than originally assumed. The problems with the letters D and K arose from a discrepancy between the photographs of the standard signs from which the programming was determined and the signs actually used by deaf-blind people.

The consultants advised that the hand was overly large and needed to be curved like the human hand. Both consultants indicated that more force was needed to simulate action of the human hand. The consultants also felt that the hand would need a lifelike glove to provide a more natural "feel."

4. Apparent Potential of the Mechanical Hand

Based upon the results of this first effort, it was felt that a mechanical hand for forming the one-hand manual alphabet at conversational speeds was feasible. As a result of discussions with the deaf-blind consultants, interpreters, and educators of the deaf-blind, a variety of potential applications were seen. These are as follows:

- A simple communication device to allow non-signers to communicate with deaf-blind people both at home and at work.
- An educational device for teaching deaf-blind children sign language and enabling a single teacher to lecture several students simultaneously.

- o A "talking book" driven by a tape recorder.

- o A telecommunicator which would connect through the telephone to teletype machines or other mechanical hands.

5. Patent Application

During the initial program, a thorough patent search was made; related patents were reviewed and shown to be non-conflicting. A patent application was subsequently submitted and Patent No. 4074444 was granted on 21 February 1978.

III. FURTHER DEVELOPMENT OF A MECHANICAL HAND FOR COMMUNICATING WITH DEAF-BLIND PEOPLE

A. Design Considerations

The performance of the original mechanical hand dictated in large part the plan for development of the improved version. Prior to initiating the design, a study was performed to develop a standard set of characters for the one-hand manual alphabet and the hand and finger motions required to form them. A study was also made to determine what hand size, shape and inclination was most easily read by the deaf-blind.

B. Standardization of One-Hand Manual Alphabet

During the prototype development program, it was noticed that the deaf-blind consultants had difficulty in recognizing mechanical sumbols that agreed quite well with published pictures of the symbols. Deviations in formation of the signs were also noted between deaf-blind persons and between interpreters. Very often these differences were between people educated at different schools or those from different geographical regions. It also appeared that the motion of the sender's hand influenced recognition of the symbol in addition to the static sign itself. The deaf-blind consultants often had difficulty recognizing a static sign but, when they felt it being formed, it was easily recognized. The attitude of the hand, whether rotated or inclined, also appeared to be of significant importance.

In order to determine the most universal signs and methods for making them, members of the design team visited the National Center for Deaf-Blind Youths and Adults in Sands Point, New York, San Antonio College's staff of interpreters for deaf students, and Southwest Center for the Hearing Impaired in San Antonio. Members of the staffs of these organizations were interviewed and asked to form the characters of the one-hand manual alphabet. Communication between signers was also observed. A tool of incalculable value was provided by Dr. Frederick M. Kruger of NCDBYA. This was a video tape of one of the Center's interpreters illustrating the signs and methods of communicating with the deaf-blind. The interpreter was selected by deaf-blind clients at the Center as being the easiest to read.

The analysis of this video tape and observation of other interpreters produced the following conclusions:

(1) Differences in finger spelling do exist. These differences are small and for the most part are caused by differences in hand anatomy and mobility. There also appears to be a difference between people who communicate primarily with deaf people and those who communicate primarily with deaf-blind people. The hand symbols of deaf-blind communicators

tend to be more compact (greater curling of the fingers in intermediate positions) than deaf communicators. The deaf communicators also tend to present their symbols in a more upright position.

(2) Deaf-blind communicators enhance the readability of the static sign by cueing and by presenting it in its most easily read position. Examples of cueing include grasping the thumb of the reader with the index and middle fingers when forming N and adding the ring finger to the grasp for M. Advantageous positioning is used particularly with the letters A, S, and E in which the primary discriminator is the position of the thumb relative to the flexed fingers. For these signs, the hand of the signer is inclined upward and thrust into the palm so that the reader can discriminate the thumb. This cueing and presentation is done primarily through wrist rotation and flexion.

(3) Deaf-blind communicators strive to minimize the amount of motion the hand of the reader must have to follow the hand of the sender. Rather than the reader following the sender, the hand of the sender "hunts" the hand of the receiver. If the hands must separate, as is needed in finger extension, the sender moves his hand away and then back into the hand of the receiver. This requires use of the elbow as well as the wrist.

(4) Deaf-blind communicators establish and maintain a rhythm in producing signs. They also adapt their signing rate to the skill of the individual reader.

(5) There is a wide variation between readers in the position they hold their hand relative to the hand of the sender. The majority read in a face-to-face position with their arm and hand in line with the hand of the sender. Others prefer that their hands be at an angle to the hand of the sender with the fingers of the sender against the palm. In this position, the fingers of the receiver reach over the hand of the sender to detect the location of the thumb. An example of this position is shown in Figure 1. Still others position themselves beside the sender with their arm and hand roughly parallel to the sender's. In this position, the receiver detects thumb motion with the little and ring-fingers and finger position with the thumb, index and middle fingers. An alternate hand position when side by side is sitting arm-in-arm with the palm of the receiver up. In this case, the sender signs downward into the hand of the receiver.

(6) Deaf-blind communicators tend to use only four basic finger positions in signing: extended, partially flexed, flexed, and a limited flexion. The limited flexion is used only for the letter E and consists of flexing the last two segments of the fingers while keeping the segment nearest the palm fully extended.

(7) Deaf-blind communicators primarily utilize wrist flexion and arm rotation in differentiating symbols having similar finger conformation. Side motions of the hand are only used for cueing and improving the presentation of the symbol with the possible exception of the letter Z. The side-to-side motion of the index finger is sometimes produced by moving the entire hand, although most of our consultants agreed that moving only the index finger was preferred.

(8) In efficient finger spelling, the communicator presents words or syllables rather than discrete letters, i.e., THE rather than T, H, E. There is a general melding of letters to form recognizable words as in speech which improves recognition by the reader. It also alters to some extent the symbol actually presented in that the hand never stops moving during the course of the word; it is questionable whether the ideal static sign is ever precisely formed.

The video tape was also used in developing the initial programming of the mechanical hand. The finger positions needed for each letter were classified as flexed, extended, partially flexed or as limited flex. Confirmation of these positions were made by having a person unfamiliar with the manual alphabet form each letter according to the derived table. Their hand symbol was then compared to the symbol shown on the tape. These device symbols were also reviewed by our consultants and their suggestions incorporated into the table.

In addition to the static finger positions, it was also necessary to determine the motion the fingers must have to avoid obstructing motion of other fingers. This was accomplished using the video tape and manually simulating the formation of each leter. Formation of each letter starting from the "rest" position was the only mode considered in this initial study. The code developed from this study is shown in Figure 5.

It was realized that other finger interactions would occur when moving from letter to letter. Rather than considering all the possibilities at this early stage in the development program, it was decided to wait until the hand was completed and to identify letter-to-letter interactions as they occurred. Knowing the interactions prior to the design phase would have been of little benefit since correcting them is done by reprogramming and not by design changes. These observations had a major influence on the

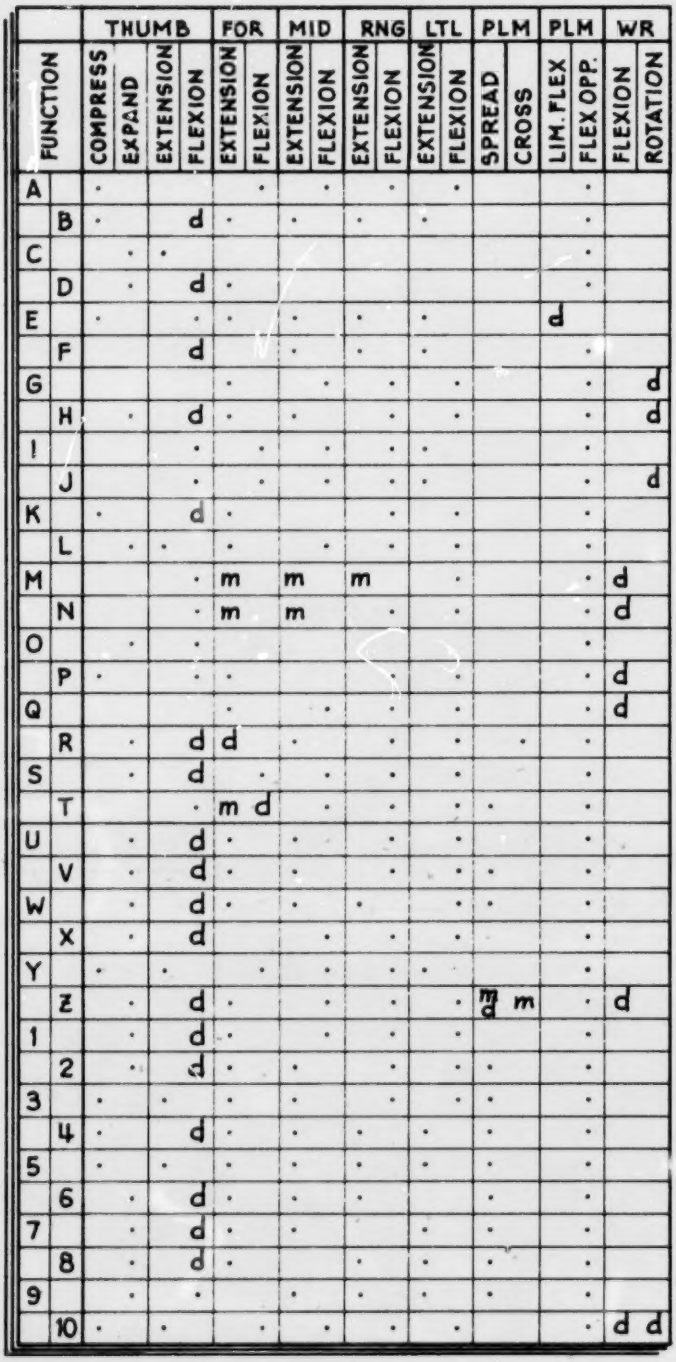


FIGURE 5. ONE-HAND MANUAL ALPHABET FINGER POSITION CODES FOR THE MECHANICAL HAND

final design of the hand. These will be pointed out later in the discussion of the design criteria and the design itself.

C. Hand Shape and Size Study

In response to criticisms by deaf-blind consultants regarding size and shape of the prototype mechanical hand, a study was made to determine optimum size and shape for the advanced prototype hand. The resources of the program did not allow an extensive, formalized study of the shape, size, and anatomical characteristics of the hand which influence symbol recognition. Instead, deaf-blind individuals at each organization visited were asked to identify one or two people they thought had the most easily read hand size and shape.

The hands of the identified people were measured and recorded. Measurements included overall hand length, breadth, and the individual finger segment lengths. A total of seven hands were measured (and it should be noted all were women's hands) and the averages of each of the measurements computed. Rather than using these averages as the mechanical hand dimensions, the specific hand most closely approximating the "average best" hand was selected from among the hands measured. While this hand does not identically match the "average best" hand, it was felt that selection of a specific hand would aid cosmetology of the hand. It was felt that the selected hand could be used as a model for molding the cosmetic covering. This would facilitate production of a covering since the glove would have the same nominal dimensions as the underlying mechanical hand.

Once the specific hand had been selected, it was remeasured in greater detail. In addition to the dimensions, the angles of the fingers and their joints relative to the palm were determined. The nominal curvature of the palm was also determined when all the fingers were touching the thumb. This hand curvature was selected since nearly all signs have one or more fingers flexed or partially flexed and the palm curvature varies with the flexure of the fingers. Note: The dimensions of the hand used are shown in Figure 6.

D. Design Criteria

The design studies produced the following design criteria:

1. The hand should be the nominal size and shape of a nominal 50th percentile woman's hand.

2. The fingers should be fully articulated, i.e., three segments.

3. Four discrete finger positions were needed; extended, partially flexed, fully flexed, and a position combining extension of the first segment and flexion of the two end segments.

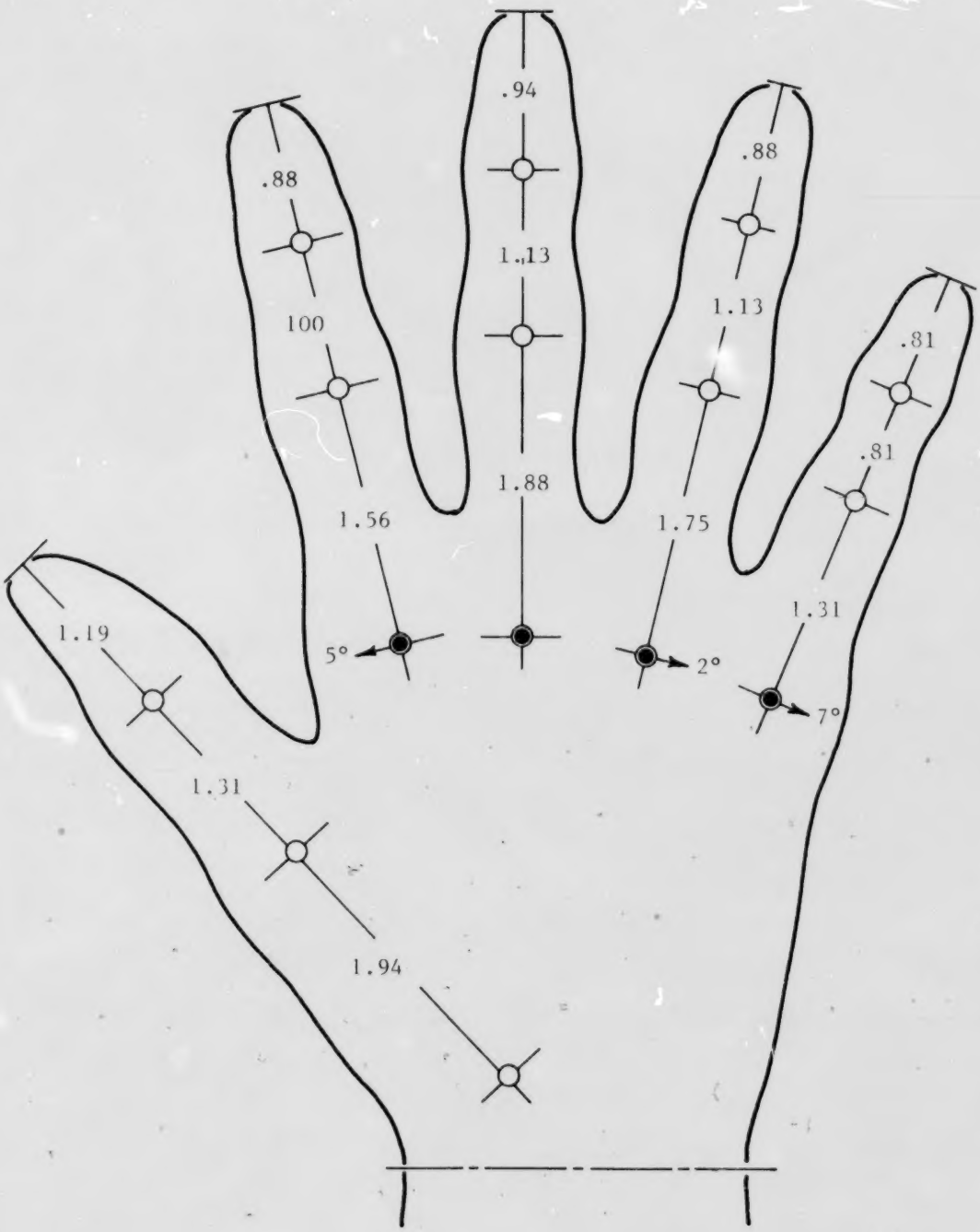


FIGURE 6. MECHANICAL HAND DIMENSIONS

4. The index finger, ring finger, and little finger must be able to spread relative to the middle finger.

5. The index finger must be able to cross under the middle finger.

6. The thumb must have three positions in flexure and three different inclinations relative to the palm.

7. The wrist must flex at least 45° and preferably 90°.

8. The hand must rotate about its longitudinal axis.

9. There must be little change in finger position during hand rotation or wrist flexure.

10. The hand should be capable of forming at least two characters per second (24 words/minute).

11. The hand should have a lifelike cosmetic covering.

12. The control electronics must be readily reprogrammable to provide refinement and modification of the symbols.

13. To the greatest extent possible, the components used in the hand should be readily available from commercial sources. The use of exotic or high cost technology should be avoided. Designed components should be amenable to low-cost replication.

E. Design Description

1. Hand Assembly

The mechanical hand assembly shown in Figure 7, consists of a driver sub-assembly, a rotatable forearm, and the hand which is attached to the forearm through a wrist mechanism. The driver sub-assembly seen from the side in Figure 8, consists of two modules in aluminum boxes which are four inches square and ten inches long. The boxes are open and a portion of the top and bottom are cut out to provide access to the interiors. Each box contains eight linear solenoids which drive the fingers and thumb. A rotary solenoid for rotating the arm is attached to the rear end bracket. Another rotary solenoid, for flexing the wrist, is attached to the top of the driver sub-assembly.

Solenoids were chosen as the actuating device after a thorough investigation of possible devices. Pneumatic and hydraulic devices were eliminated because of the need for a pressure source. The need to transport the device required minimizing system weight and the added weight and bulk of an air or hydraulic compressor was felt to be unjustifiable. Additionally, such systems are prone to leaks if frequently disconnected and moved. This would cause high maintenance costs and, in the case of hydraulics, a potentially hazardous and unsightly situation.

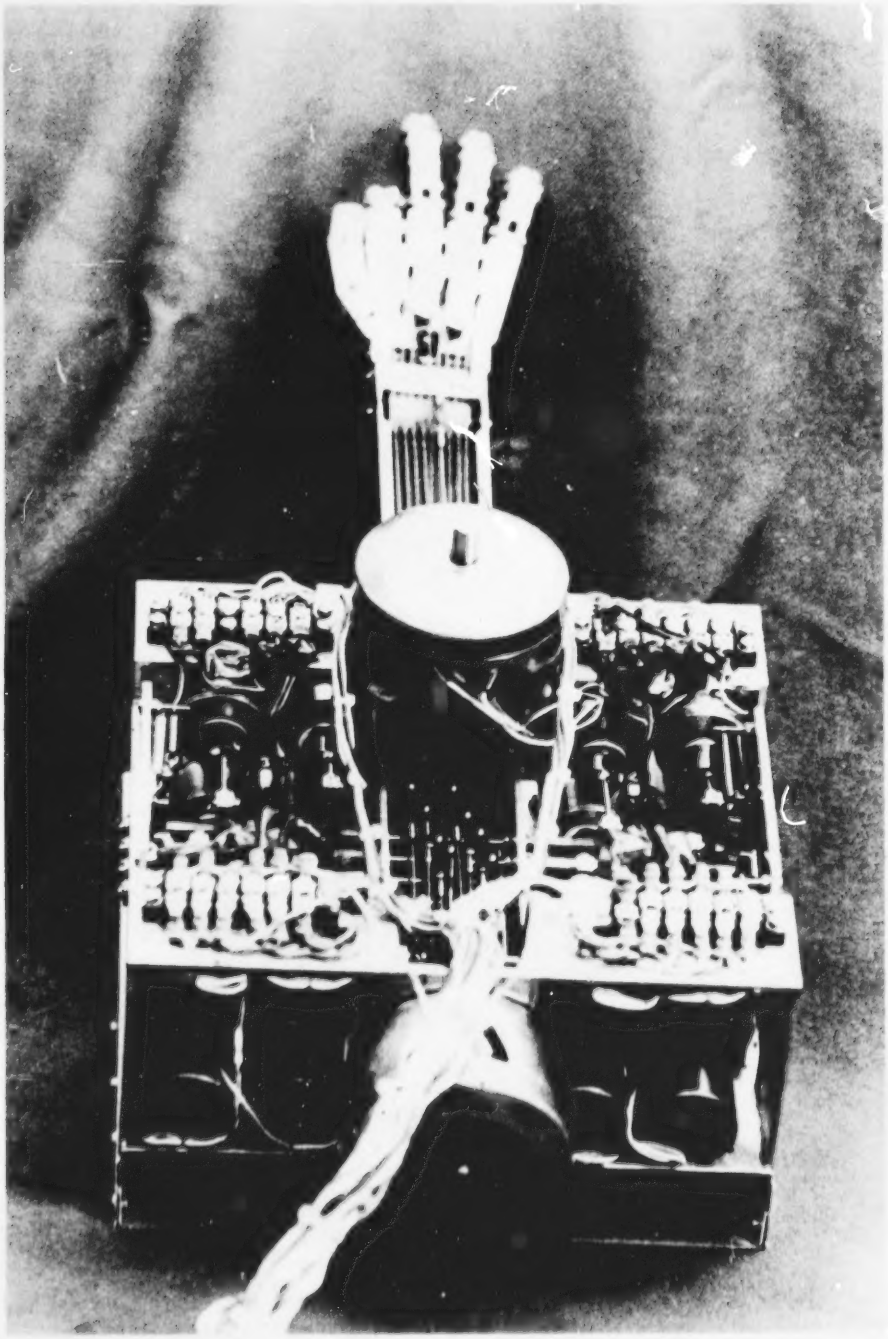


FIGURE 7. THE IMPROVED MECHANICAL HAND
AS SEEN FROM THE REAR

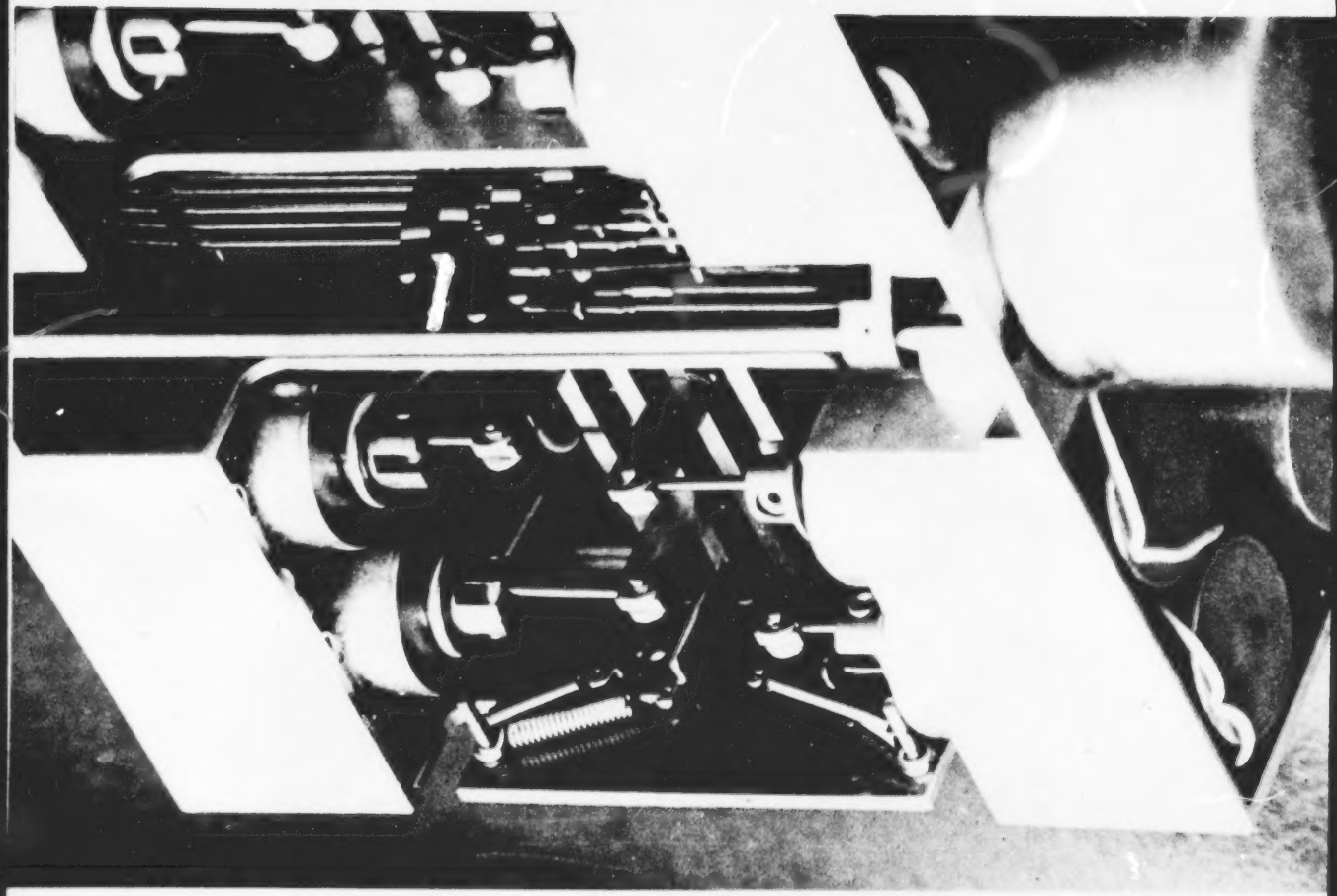


FIGURE 8. DRIVER ASSEMBLY DETAIL

Of the electrical devices available, solenoids (both linear and rotary), motors, and stepping motors were considered. The stepping motor has the greatest force production of these devices. While the average power is small, stepping relays require short, high current pulses to step. This requires a special power supply or, for self-stepping models, a high capacity supply. Since at least nine stepping motors would be needed, the power needed was above the level available from most standard outlets. Secondly, the control electronics would have inordinately increased the cost of the machine.

Small electric motors were eliminated since they required gear boxes and clutches. The cost of motor, gearing and clutches, would have also been excessively high and packaging the nine sets would have been very difficult.

The advantages of the linear solenoid as the finger actuator were their compact size; high force capability; the ability to change their force by simply changing their voltage; and their amenability to simple linkage systems. They are, however, heavy. This was felt to be of secondary importance in this version of the hand since it is primarily a test bed for the hand itself. Adequate force was needed to insure operation of the hand at a conversational rate even though the system might only be semi-portable.

The linear solenoids are attached to the inside of the top and bottom of the boxes, one above the other. The solenoids face each other so that the plungers point in toward the center. Each pair of plungers, an upper and a lower, is connected through adjustable links to a rocker arm. Each rocker arm is mounted on one of four shafts which cross the box and protrude part way into the cavity between the two modules. The rocker arm shafts are made of 3/16" square steel keystock. The ends of the shafts are turned down to a 1/8" diameter so they can turn freely in flanged bronze bearings mounted in the sides of the box sections. The solenoid rocker arms have square holes through which the square shaft fits, providing a non-rotating union to improve the system's reliability.

Another rocker arm is secured to the cavity end of the shaft with a screw and lockwasher. The end of the shaft is squared to mate with the squared hole in the rocker arm, referred to hereafter as the cable rocker arm. The cable rocker arm, made of 1/16" thick stainless steel plate, has its ends offset from the center of the arm by 1/16".

The ends of the cable rocker arm are drilled to accept two snap clevises similar to those used in model airplanes. The clevises are screwed onto threaded cable terminals to provide an adjustment of cable length. The cables transmit the pull of the solenoids to the fingers and thumb and are routed over a series of pulleys as illustrated in Figure 9. The cables leave the rocker arms toward the rear of the driver assembly central cavity. Near the rear of the cavity they pass around a series of pulleys which reverse them toward the hand. Near

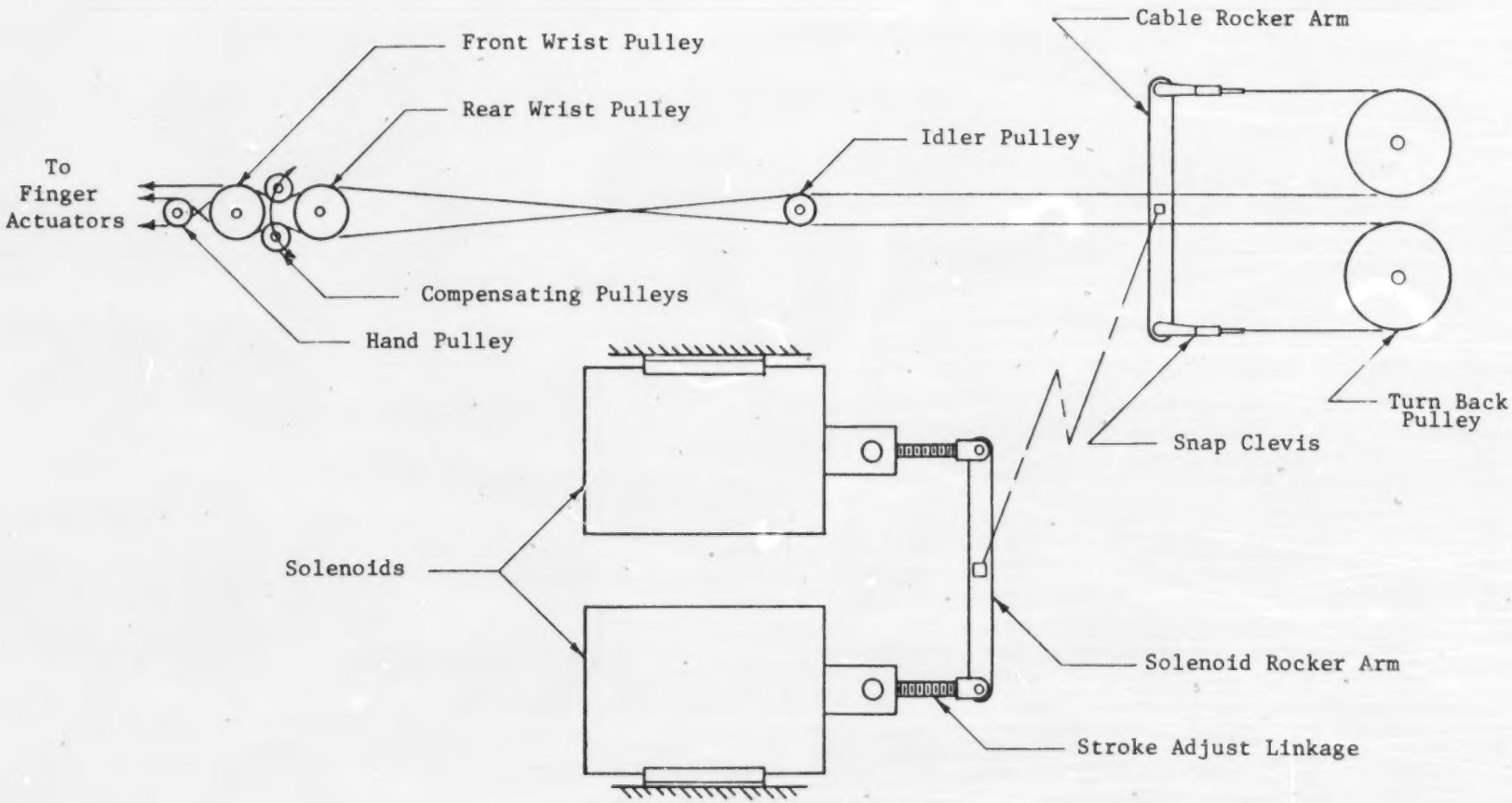


FIGURE 9. FINGER CABLE RUN SCHEMATIC

the front of the cavity, the cables pass over another series of pulleys before leaving the driver assembly and entering the forearm. The upper and lower cables cross as they traverse the forearm before reaching the first row of wrist pulleys.

In the wrist, the cables pass across two rows of large pulleys and between two sets of smaller pulleys mounted on a frame pivoted on the fixed shaft of the rear set of large pulleys. These small pulleys force the upper and lower cables inward. This arrangement is the key to the operation of the wrist and its function will be described later.

The front row of large pulleys is mounted on the same shaft as the hand itself. The cables, after passing over the front row of pulleys, proceed to the finger actuators. The lower cables pass over a fixed row of pulleys in the hand which directs them from under the palm to the top of the palm where they enter the finger actuators. The cables for the thumb, finger spread/cross mechanism, and for the limited flex mechanism follow essentially the same path from the solenoids.

2. Finger Design

The fingers of the artificial hand have three segments equivalent to the proximal, middle and distal phalanges of a human hand as shown in Figure 10. All four fingers are identical except in the lengths of the first and second segments. Segments are fastened to each other by 1/8" diameter steel hinge pins. Additionally, the segments are interconnected by two Delrin™ links; one in the first segment and one in the second segment. These links are arranged such that, as the first segment rotates relative to the palm, the second and third segments rotate an equal angle about their hinge pins. This produces a uniform curling of the fingers as they move from fully extended to fully flexed.

The links are located along the mid-plane of the finger. The sides of each finger segment are 1/16" thick aluminum plates laminated together by two screws and nuts. Spacers are inserted between the two sides to allow sliding clearance for the interconnecting link. It should be noted that 32 lamina are used in fabricating the fingers, but only four basic designs are used and the only variation between fingers is overall length. The design is such that the plates can be inexpensively die stamped using a series of three dies, one cutoff operation, and two drilling operations.

The "rest" position of the finger is governed by springs located in the finger and driver assembly which are pretensioned to position the finger at midflex. Finger position is controlled by a single push-pull link attached to the rear upper corner of the first finger segment. When pushed, it rotates the finger downward into the flexed position; when pulled, it extends the segment. As the first segment rotates, the first segment connecting link (attached to the

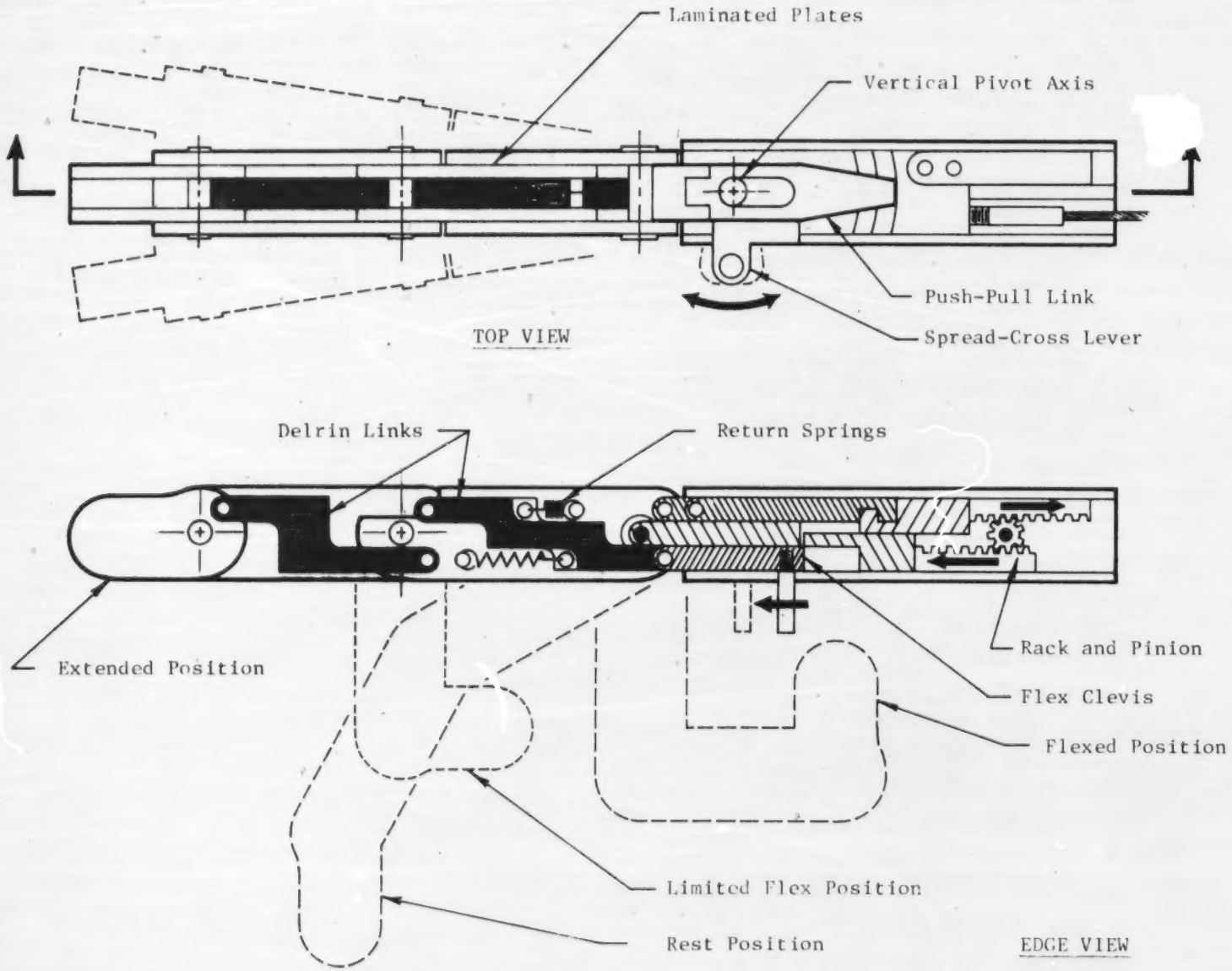


FIGURE 10. FINGER MECHANISM

palm at one end and to the top rear corner of the second segment) forces the second segment to rotate about its connection with the first segment. The location of the link attachment points relative to the segment hinge pins governs the relative rotation of successive segments. In this design, they are placed 90° away from the push link which produces equal rotation of the succeeding segment. The second segment link connects the first and third segments in the same manner as the first segment link.

The finger push-pull rod is actuated by two cable pulls. The cables each attach to sliding rack gears separated by a stationary pinion gear. All three elements are enclosed in an aluminum housing. The push-pull rod is connected to the upper rack gear. When the upper rack gear is pulled by the cable, it moves rearward pulling the finger into its extended position. A pull on the lower cable moves the lower rack rearward, rotating the pinion gear. This drives the upper rack forward rotating the finger into the flexed position.

As mentioned earlier, the first segment connecting link is fixed at one end to the palm by a clevis. This clevis is in fact a sliding link inside the finger actuator assembly. A dowel pin fitted into the link protrudes through a slot in the bottom of the actuator assembly and through a mating slot in the palm plate. The pins of all four fingers fit into a sliding block made of Delrin on the underside of the palm plate as shown in Figure 17.

The plate's position is controlled by two cables which slide it forward and backward. When in the rearward position, the flex clevis is in its normal position to produce uniform flexure of the fingers. When the clevis is moved forward, however, it produces a different behavior in the second and third finger segments; i.e., when the first segment is in extension, the second and third are flexed. The case where the first segment is extended and the second and third are flexed (called the "limited flex" position) is required to form the letter E.

A second, T shaped sliding plate, also shown in Figure 17 and similar to the limited flex plate, is also attached to the underside of the palm plate. This plate, also controlled by two opposing cables, produces finger spreading and crossing. The attachment bracket for the finger is pivoted about a vertical shaft in the actuator housing. An arm of the bracket extends through a slot in the side of the actuator housing. A shaft screws into this arm and passes through slots in the palm plate and limited flex plate and fits into a hole in the finger-spread/cross plate.

When the finger-spread/cross plate is pulled forward, the fingers spread. When it is pulled rearward, it rotates the fingers inward. The shaping of the hole for the index finger is different than that for the other fingers so that it will rotate inward more than the other fingers. This provides the ability to cross the index and middle fingers.

3. Thumb Design

The design of the thumb and its operation are essentially the same as the fingers. The thumb is shown in detail in Figure 11. It consists of three laminated segments with interconnecting links. The links produce equal angular rotation of each segment relative to the preceding segment. The major difference in the thumb is that the flexion/extension cables attach directly to the first thumb segment rather than through an actuating mechanism. The first segment contains a combination cable clamp and tension adjustment for terminating the cable. When the extension cable is pulled, the thumb moves away from the fingers to a "thumbs up" or "hitch hiker" position. The flexion cable moves the thumb across the face of the palm until the thumb's tip is near the base of the little finger.

The thumb is attached to the palm plate by a hinge mechanism. The thumb rotates about this hinge as it flexes and extends. The alignment of this hinge allows the thumb to sweep across the face of the palm. A second hinge governs the inclination of the thumb to the palm and the plane of motion in flexion/extension. Two cables control the hinge. The first cable pulls the thumb toward the palm so that the thumb sweeps through a plane parallel to the palm. The second cable inclines the thumb away from the palm and positions the flexion/extension plane at an oblique angle. This plane is arranged such that the third segment of the thumb will contact the third segment of any finger which is in the "rest" position. This provides the finger tip touching required in forming numerals.

All four of the control cables for the thumb are pretensioned with springs to hold it in an intermediate "rest" position. The flexion/extension cables are tensioned so the thumb is partially flexed, the second segment being roughly parallel with the index finger. The thumb inclination cables are set so that the third segment of the thumb will touch the middle segment of the resting middle finger when the thumb is flexed. The use of flexion/extension planes which intersect the resting finger tips greatly simplifies the design of the hand mechanism and minimizes the number of discrete positions the thumb must attain. Since the planes of motion of the thumb and fingers intersect, finger touching by the thumb is easily attained by letting the thumb's flexion be stopped when it touches the desired finger. As an example, the letter O requires that the thumb touch the tip of the partially flexed index finger. To do this, the fingers are left in the "rest" position, the thumb inclined away from the palm and then flexed. The thumb flexes until it strikes the tip of the index finger.

If it is desired that the thumb touch another finger tip, the fingers between the thumb and the desired finger are lifted out of the way by extending them while the thumb passes across their rest position. The thumb then flexes until it strikes the desired finger and its motion

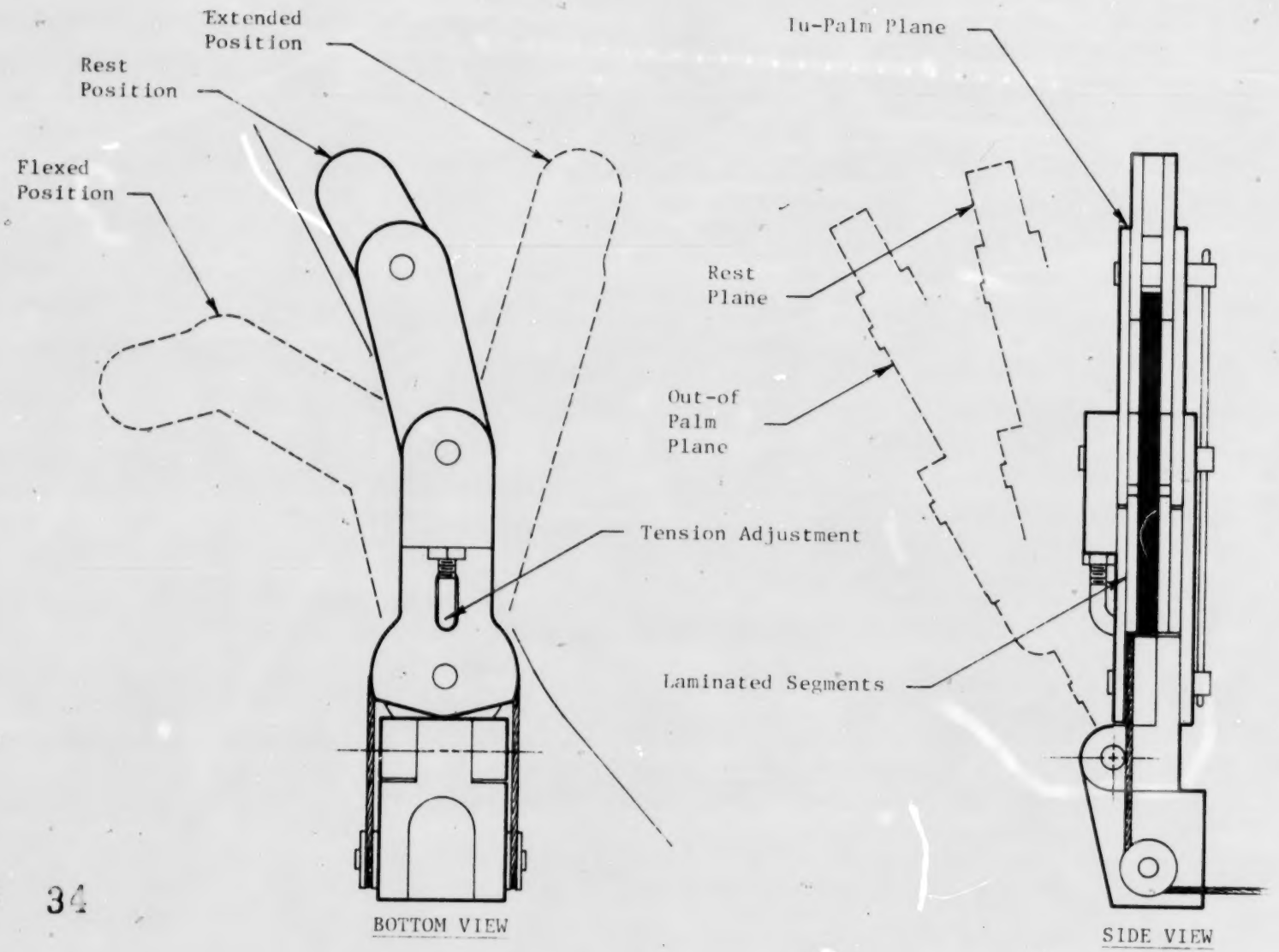


FIGURE 11. THUMB DETAIL

is halted. The extension of the intervening fingers need only be momentary as in the letter N. To form N, the index and middle fingers are momentarily raised while the thumb passes under them, stopping against the ring finger. The index and middle fingers are then released. The motion takes somewhat less than one half second to accomplish.

4. Palm Plate

The components of the mechanical hand are mounted on an aluminum plate which has the nominal shape of a resting human palm. The finger actuating mechanisms for the four fingers are attached to the top surface of the plate. The top surface is facetted to incline the finger actuator assemblies giving the upper surface of the hand a lifelike curvature. The thumb hinge mechanism is mounted on the flat bottom surface along with the limited-flex and finger-spread/cross slides. The palm plate has at its back edge two bearing flanges into which ball bearings are pressed. The wrist shaft passes through these bearings. A second shaft immediately in front of the bearing flange plates carries a series of pulleys for directing the cable to the finger actuators.

5. Forearm

The hand is attached to an eight-inch long forearm. The forearm is machined from a two-inch diameter stainless steel tube. The majority of the tube is removed to form two side bars much like the two bones of the human arm as can be seen in Figure 7. The ends of these bars are bored to accept ball bearings for the wrist shaft and the front pulleys of the wrist mechanism.

The end of the forearm opposite the hand (proximal) is left in its tubular form. The end of this tube is machined to a one and one-half-inch diameter to form a shoulder. Against this shoulder is fastened an external ring gear. A retaining ring groove is machined near the end of the tube. The end of the forearm fits into a flanged bronze bearing with a bronze thrust washer between the bearing flange and the ring gear. The flanged bearing fits into the channel of the driver assembly and is secured with a snap ring.

The flanged bearing and thrust washer allow the arm to rotate. The rotation is controlled by a sector gear shown in Figure 12 which meshes with the ring gear fastened to the forearm. The sector gear, located under the forearm, is mounted to a drive shaft which connects it to the rotary solenoid mounted at the rear of the driver assembly. The rotary solenoid produces a forty-five degree rotation of the forearm when actuated.

6. Wrist Mechanism

The wrist mechanism shown in Figure 13 is designed to provide both wrist flexion and cable length compensation. It consists of four

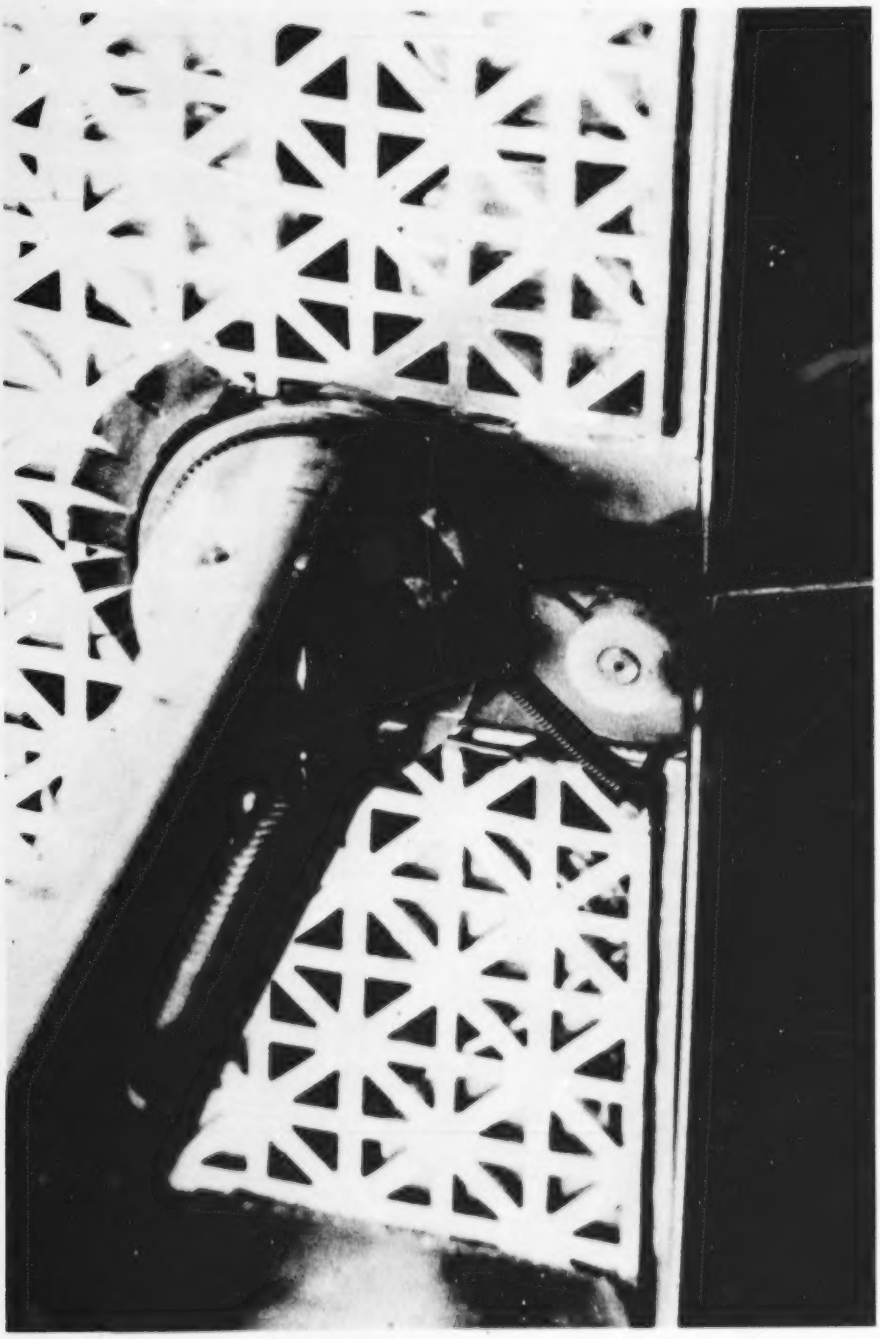


FIGURE 12. ARM ROTATOR DETAIL

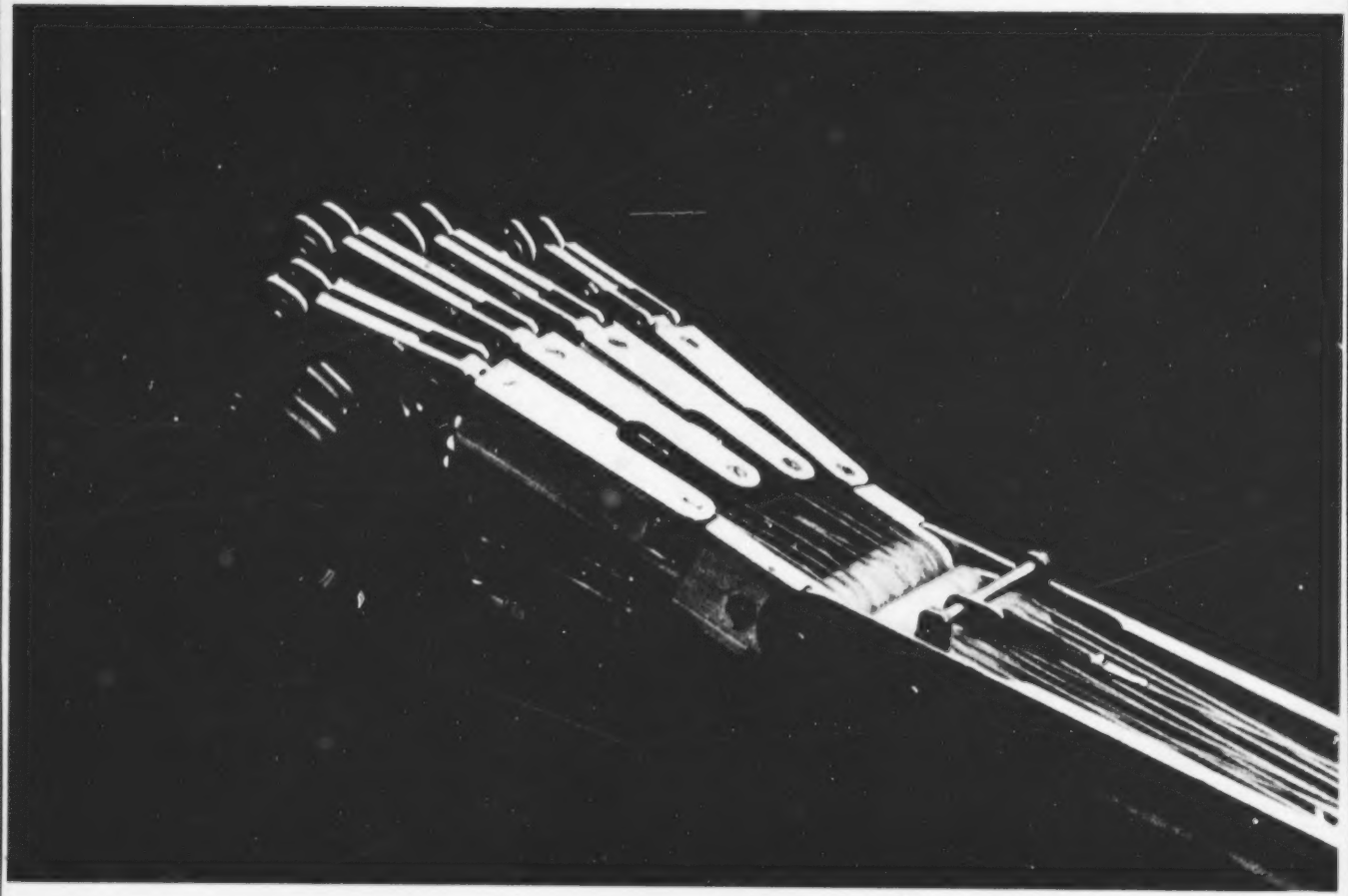


FIGURE 13. WRIST DETAIL WITH HAND FORMING THE LETTER E

rows of pulleys, two rows mounted on shafts through the forearm and two rows of smaller pulleys mounted on a rotating frame. The front row of larger pulleys are carried on the wrist shaft which attaches the hand to the forearm. The rear row of large pulleys is mounted on a shaft crossing the forearm and located one inch behind the wrist shaft.

The frame holding the two smaller rows of pulleys consist of two side plates connected by four, one-eighth-inch diameter steel shafts, press fitted and staked into the side plates. The frame's width is slightly less than the inside width of the forearm side bars. The frame is carried on the rear wrist pulley shaft about which it can rotate.

The shafts for the small pulleys are located one above the other at the front of the frame. They are positioned such that, as the frame rotates, the small pulleys will pass between the two rows of large pulleys mounted to the forearm. The other two shafts are located at the rear of the frame, one above the other and more widely separated than the pulley shafts. Sliding on these shafts are chain plates to which are attached the cables which control wrist flexure. The mechanism is illustrated in Figure 14.

The upper bar of the frame is connected by a cable to the rotary solenoid on the top of the driver assembly. The shaft of the solenoid is fitted with a cable drum for taking up the wrist flexing cable. Attached to the lower bar of the frame is a spring for returning the hand to its normal position. The spring is anchored to a shaft seen in Figure 12 through the forearm side bars near the hub of the forearm.

Attached to the same anchor shaft as the spring is one end of a cable which travels under a rear wrist pulley, between the small pulleys, under the front pulley to an anchor point on the palm plate. This is illustrated in Figure 14. The cable then runs back over the front wrist pulley, between the small pulleys and over the rear wrist pulley. The cable terminates at a second shaft through the forearm located above the original anchor shaft. Both ends of this cable are terminated with adjustable rod ends screwed into snap clevises. The cable is referred to as the wrist positioning cable.

The control cables for the hand pass over the two large rows of pulleys in the forearm, the upper cables passing over the top of the pulleys and the lower cables under the bottom. As they pass between the large pulleys, they pass between the two rows of small pulleys.

In passing between the smaller pulleys, the cables are deflected toward the centerline of the forearm. The amount of deflection is dependent on the location of the rows of small pulleys. If the frame is rotated upward by the solenoid, the deflection of the upper cable is decreased and the lower cables deflection is increased. This has the effect of shortening the lower cables and lengthening the upper cables. When the lower

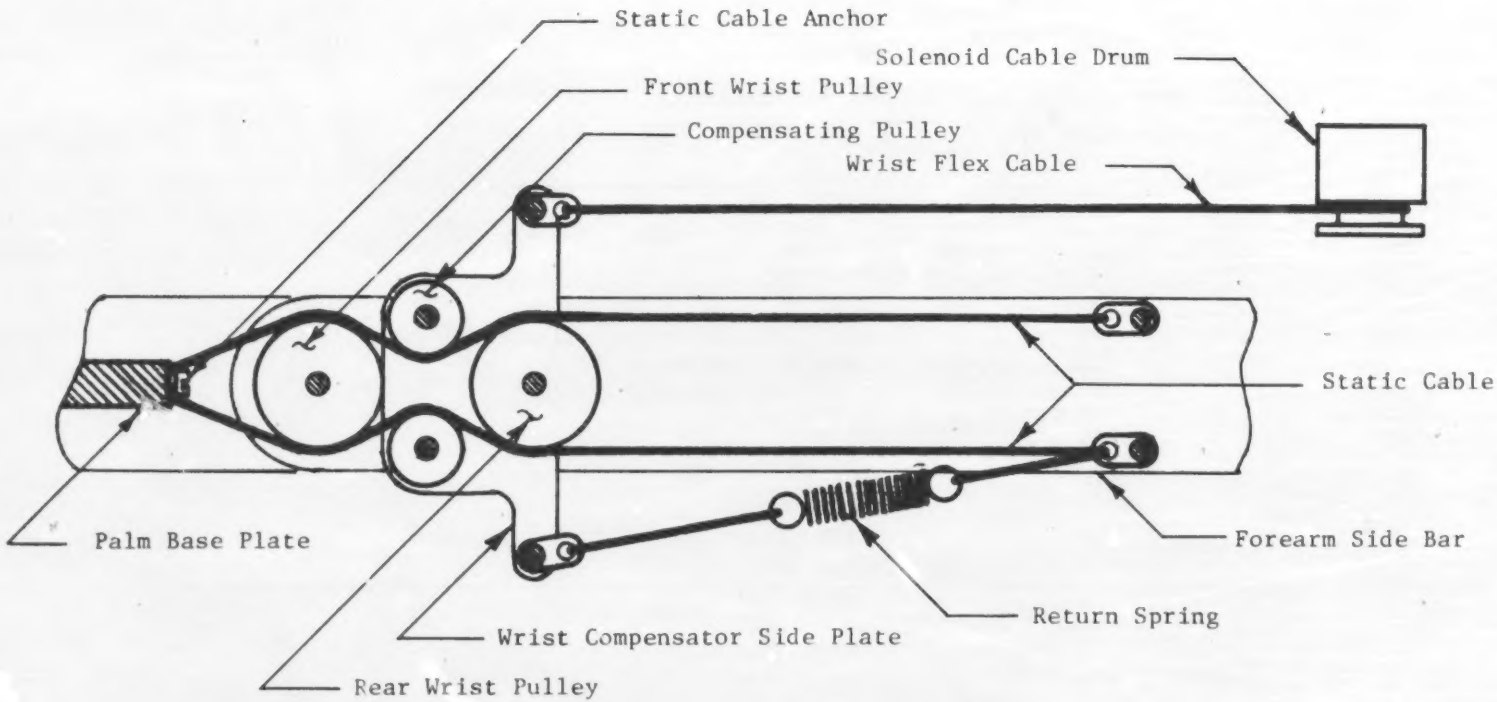


FIGURE 14. WRIST MECHANISM SCHEMATIC

wrist positioning cable is shortened, it pulls the hand downward. When the solenoid is turned off, the spring rotates the frame downward tightening the upper wrist positioning cable and slackening the lower cables. This pulls the hand up to its normal position.

Since the control cables for the fingers run through the wrist mechanism, they are also shortened or lengthened as the small pulleys move. This is necessary to accommodate for the change in cable lengths produced as the wrist flexes and prevent the unwanted changes in finger position these cable length changes produce. During flexure, the upper cables increase their degree of wrapping around the front wrist pulleys while the lower cables decrease their wrap.

Since the change in wrap is the same for all cables including the wrist position cables, the shortening of the upper cables is compensated for by the lengthening produced by the wrist mechanism; the opposite is true for the lower cables.

7. Control Electronics

The letters or numbers to be formed by the hand are selected by pressing the appropriate key of a standard electric typewriter keyboard. This produces a six bit, American Standard Code For Information Interchange (ASCII) binary code and a "strobe" signal. The ASCII code identifies the letter and the strobe signal notifies the timing and control circuits that a new character has been entered. A block diagram of the system is shown in Figure 15.

The ASCII code is decoded by specially designed logic circuitry having thirty-six outputs. Each of the output lines corresponds to a letter or a number from zero to nine. The output line corresponding to the letter selected by the keyboard is energized and remains energized until another letter is entered or until a given period of time has elapsed. The execution and holding time intervals, initiated by the keyboard strobes, are governed by an adjustable electronic timer built into the system. The holding time may be adjusted from two- to five-seconds duration.

The thirty-six outputs go to the solenoid selection matrix portion of the programming board shown in Figure 16 which is accessible by removing the rear panel of the console. The character lines terminate in a series of eighteen miniature pin jacks. The character lines are arranged horizontally across the programming board. The line for A is at the top of the board. The remaining character lines are arranged alphabetically down the board followed sequentially by the number lines.

Each character line jack is adjacent to another pin jack which penetrates the board and connects to one of eighteen lines which run vertically on the back surface of the board. These lines control the

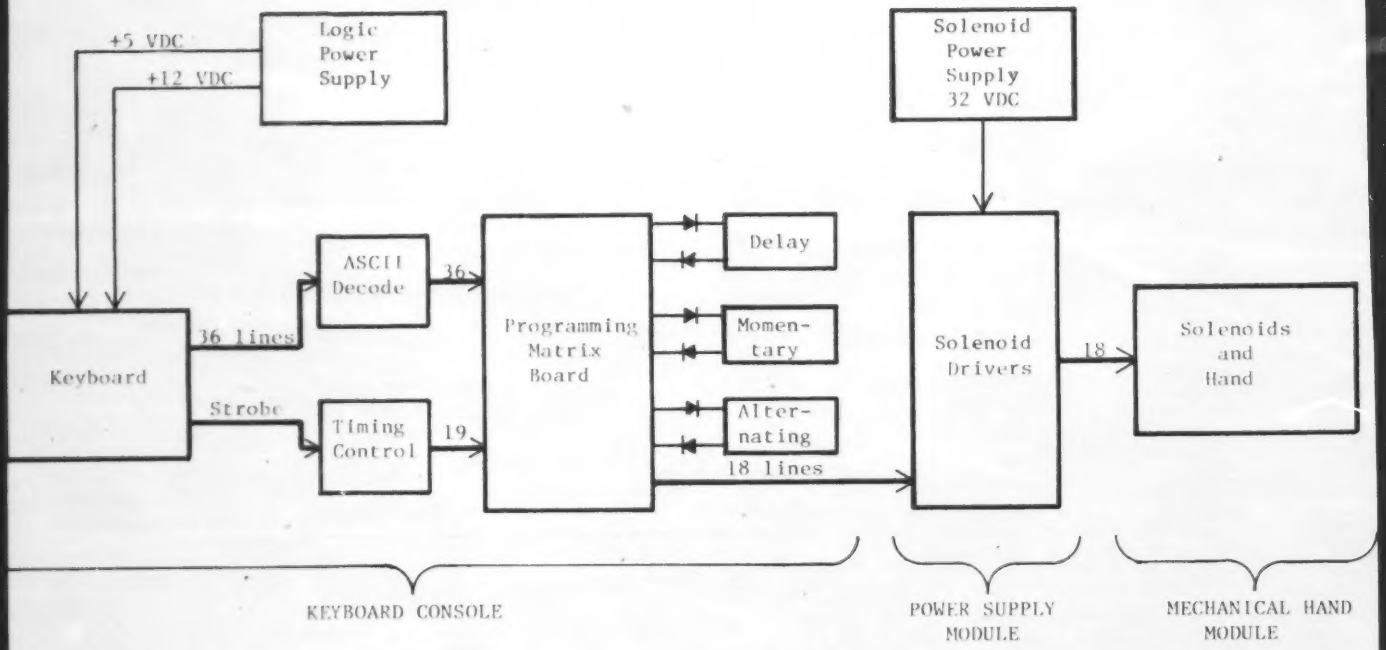


FIGURE 15. CONTROL ELECTRONICS BLOCK DIAGRAM

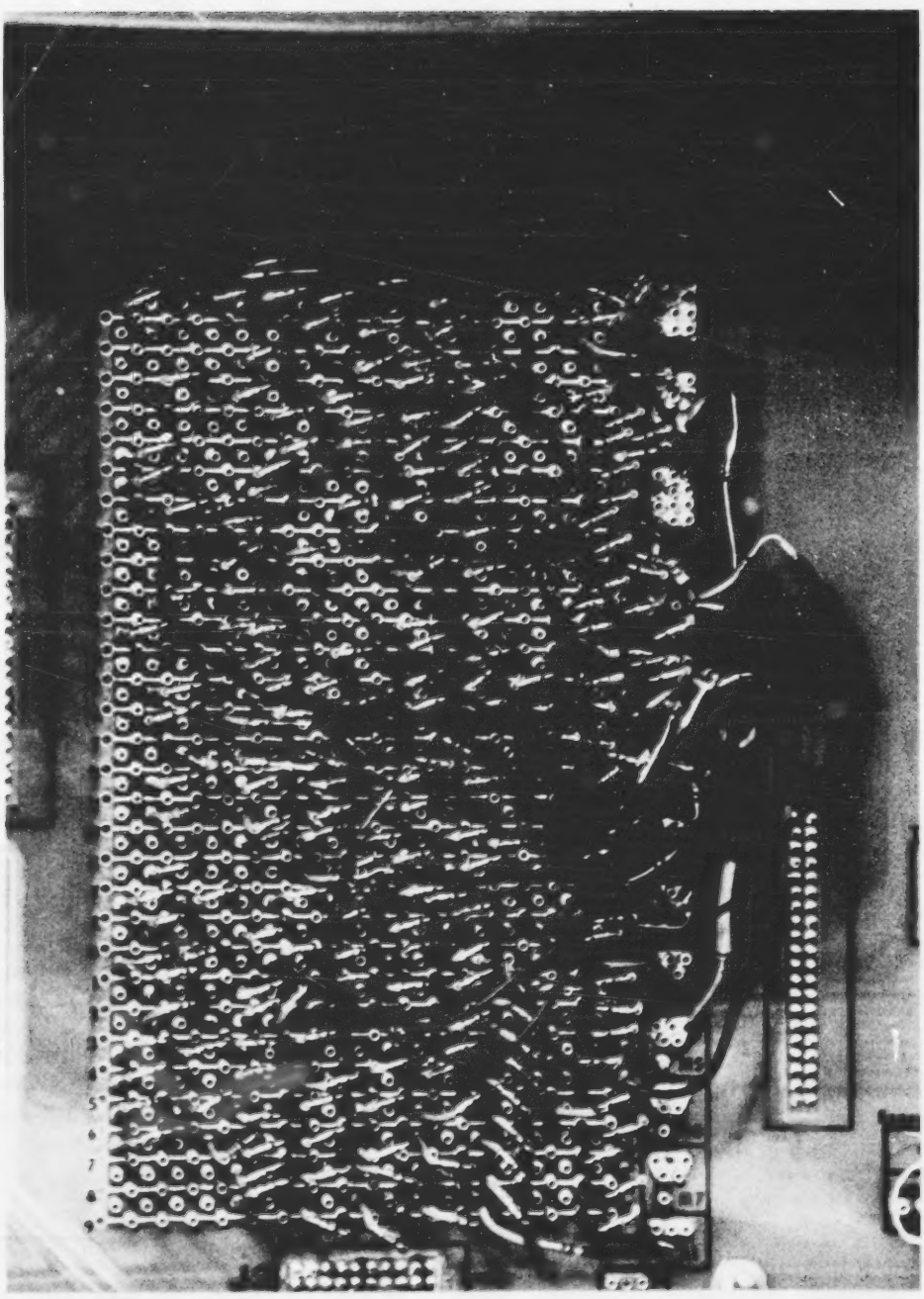


FIGURE 16. PROGRAMMING BOARD

solenoids in the hand. The lines connect to driver circuits which contain power transistors that switch the large currents needed to drive the solenoids.

The solenoid driver circuits and the 32 VDC power supply for the solenoids are contained in an enclosure separated from the hand and the keyboard. A series of lights are mounted in the front panel to indicate which solenoids are energized. The driver circuit outputs are connected to the hand by a cable which plugs into the side of the enclosure.

Selection of solenoid combinations activated for a given character is done on the programming board. To select a solenoid, a connection is made from the pin jack on the character line to the pin jack on the appropriate solenoid line. The connection is made with a diode having pins on each lead. The other solenoids needed to form a given letter are connected to that character line by additional diode jumpers.

Additional control of solenoid activation is provided by a series of timing modules located adjacent to the solenoid selection matrix on the programming board. These modules provide either (1) a delay in the activation of the solenoid after the key is pressed, (2) a momentary activation of the solenoid upon key closure, or (3) an alternating on-off-on activation of the solenoid. The modules have pin jacks to which the diode jumper from the character line is attached. The output of the delay module is then connected to the desired solenoid. The timing modules allow adjusting the movement of the fingers to prevent or insure contact of the fingers as they form the letter. The length of each delay or momentary actuation is selectable.

IV. RESULTS

A. Physical Description of Improved Prototype

The improved prototype mechanical hand for communication with deaf-blind people consists of three major components (Fig. 17).

(1) A keyboard console containing the alpha-numeric keyboard, decoding electronics, and the finger programming board. (Dimensions-12½" x 17" x 14-5/8", weight - 20 lbs.)

(2) A power supply module containing the power supply for the solenoids, the solenoid switching circuits (solenoid drivers), and an array of indicatior lights located on the front panel to identify solenoid activation. (Dimensions - 7½" x 19" x 10½", weight - 38 lbs.)

(3) The mechanical hand and its associated stand. (Dimensions - 10-1/4" x 10-1/8" x 25", weight - 33 lbs.)

The components are connected together by multiconductor cables fitted with connectors so the three units may be physicaly separated. A main power switch is located on the front of the power module. A separate power switch is provided for the keyboard console and is located adjacent to the entrance of the console's power cord.

B. Statics

The resting position of the fingers, shown in Figure 18, is governed by two opposing tension springs attached to each rocker arm shaft in the driver assembly and a similar spring couple within each finger. The inclination of the hand with respect to the gravitational vector also influences the rest position. When the hand is horizontal, the fingers have less flexion than when the hand is inclined or vertical. This is not considered detrimental since the human hand behaves in much the same way; the change in position with inclination gives, if anything, a life-like quality to the hand's performance.

The fingers, as built, do not fully flex or fully extend when driven by the solenoids. This is due to a combination of additive tolerances in the finger actuators which limits travel and which requires that the actuating cables be left somewhat slack. The slack cables require greater solenoid travel resulting in lowered force at the beginning of their stroke. It has been necessary, so far, to limit the solenoid stroke (and, therefore, the motion of the fingers) to maintain the speed of the hand at the expense of obtaining full flexure and extension. As of this writing, the fingers do come within five to ten degrees of both full flexion and extension.

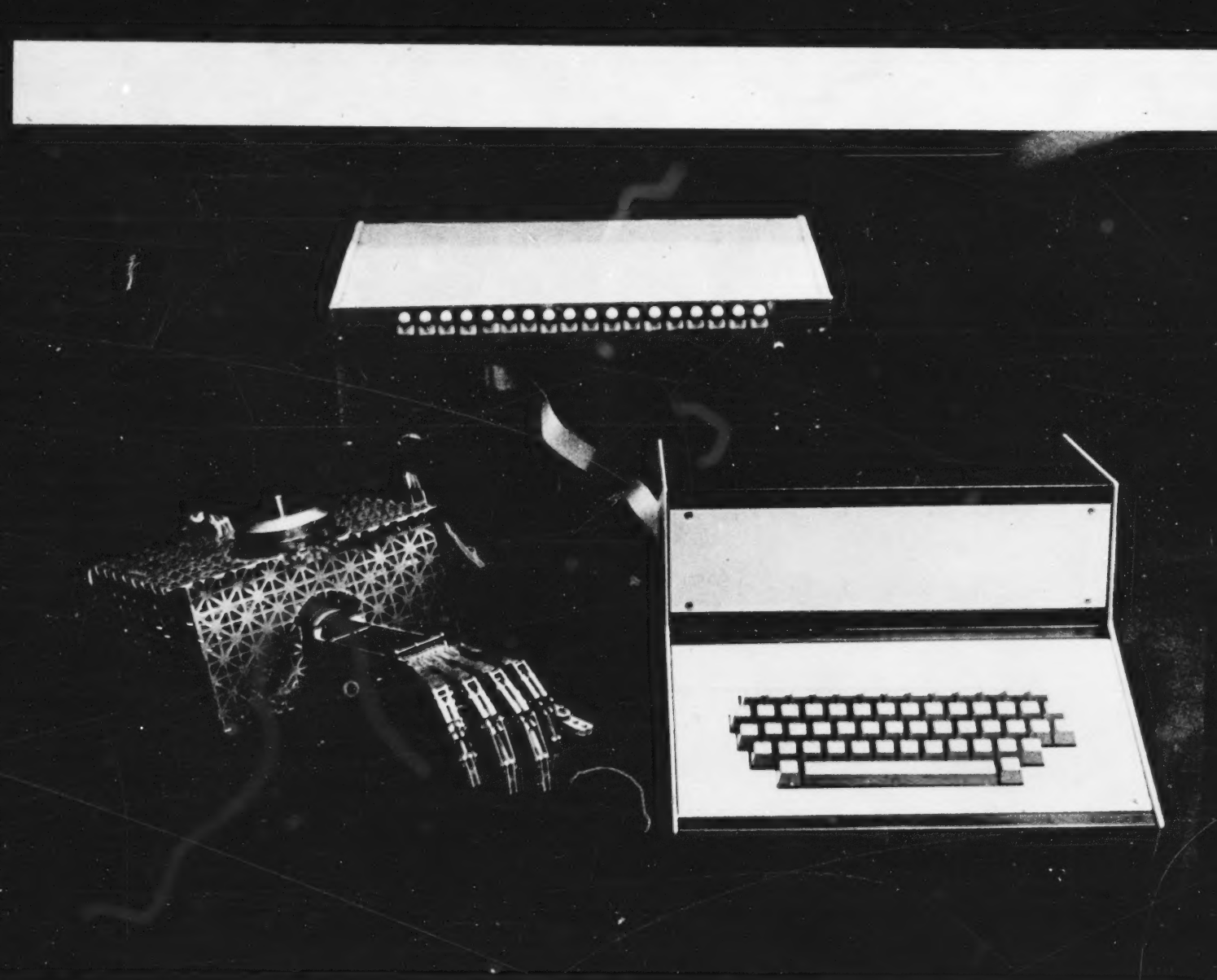
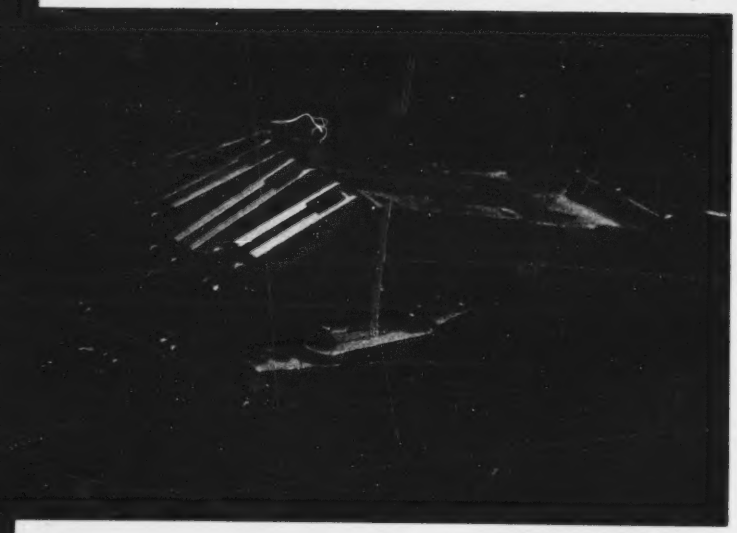
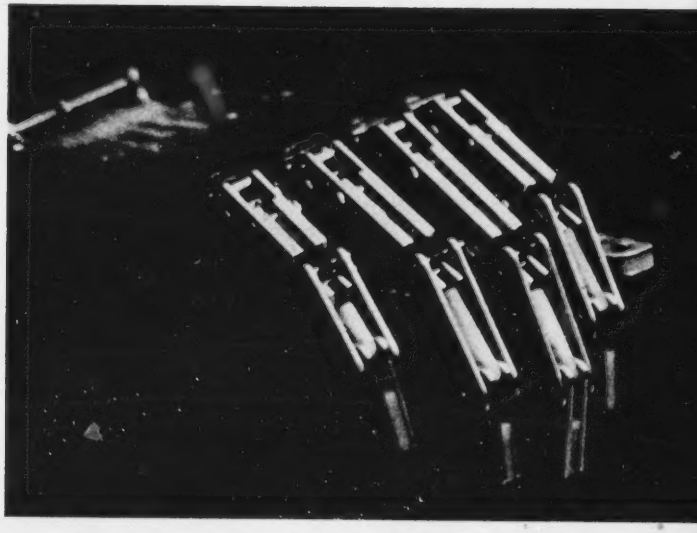
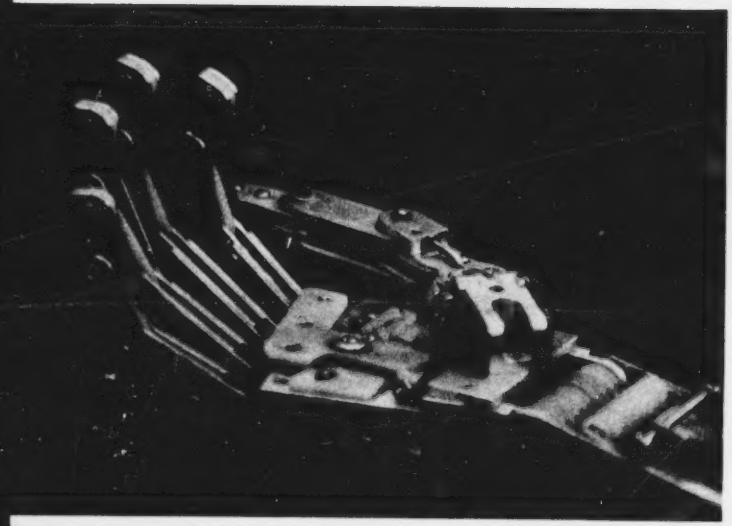


FIGURE 17. IMPROVED MECHANICAL HAND SYSTEM FOR COMMUNICATION WITH DEAF-BLIND PEOPLE







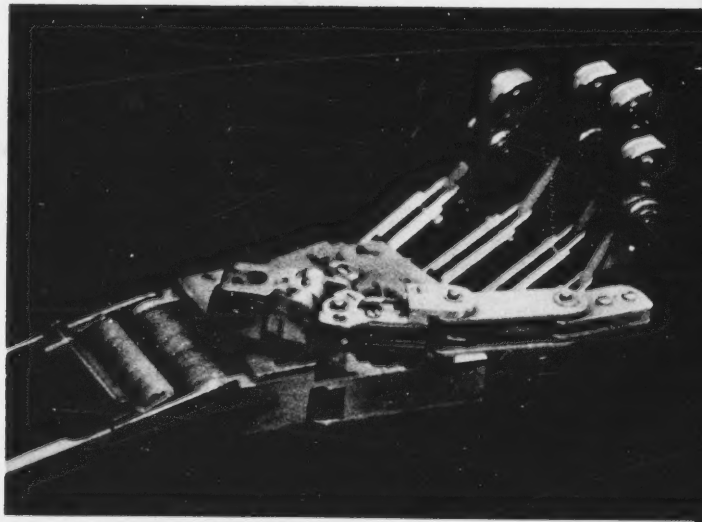


FIGURE 18. THE MECHANICAL HAND IN FOUR VIEWS

The finger spread/cross and limited-flex functions suffer from the same problem as the flexion/extension mechanism. The index finger is capable of rotating approximately eight to ten degrees either side of its neutral position; the ring and little fingers can rotate about twelve degrees either side of neutral.

The thumb has full extension but its flexion is limited to approximately half of that desired. The limitation in flexion is due to the use of mininally tensioned cables and to tolerancing problems in the thumb flex mechanism.

The thumb's inclination relative to the plane of the palm ranges from 0^{o} in one extreme to 45^{o} out of the plane of the palm in the other extreme. It was found that this was not enough to allow the thumb to flex across the flexed fingers as is needed to form the letter S . This is a dimensional problem which can be corrected by either increasing the inclination of the thumb or lengthening the first segment of the thumb.

The wrist mechanism allows the hand to move $\pm 22^{o}$ about the axis of the forearm. The rest position can be adjusted anywhere within this range. Maximum wrist flexure is 22^{o} below the forearm's axis.

The forearm rotates a maximum of 45^{o} counterclockwise as designed. The amount of rotation can be reduced by adjustment of the linkage mechanism connecting it to the rotary solenoid.

C. Dynamics

The speed of the hand in forming letters is variable, depending on the complexity of the symbol formation and whether wrist flexure and arm rotation are needed. Arm rotation is the slowest function due to the large inertia of the arm and hand assembly. Within the hand, limited flex is the slowest function followed by thumb flexure. While precise measurements have not been made, most simple symbols can be formed in 0.5 to 0.75 seconds.

Symbols which require momentary or delayed movements require somewhat more time to form than those requiring only flexure or extension of the digits. This is inherent and may present problems if letters are entered too rapidly.

As mentioned previously, it was anticipated that there would be detrimental interaction of digits when moving from one letter to another. This does, indeed, occur. There has not been adequate time to catalogue these interactions or to provide the reprogramming necessary to prevent the interactions.

D. Consultant Reactions

The unanticipated level of design and fabrication effort required to produce the improved prototype left too little time and resources for

"debugging" the device or for extensive evaluation by our deaf-blind consultants. The hand was, however, shown to one deaf-blind consultant and to Dr. Fred Kruger of the NCBYA.

The deaf-blind consultant was able to identify about seventeen letters reliably. He disagreed with the finger positions in some letters and he had difficulty following the hand when it flexed or rotated. The demonstration was made without a cosmetic covering and the exposed mechanisms felt foreign to him. It also appeared that the hand could move faster than he could read it if letters were entered very rapidly.

The mechanical hand was also demonstrated to Dr. Fred Kruger on 30 March 1978, in Ft. Worth, Texas, at the Texas Society of Interpreters for the Deaf Conference. Dr. Kruger was complimentary of the significant improvements made in this program. He did feel that the less than full extension and flexion should be corrected and that the finger spread and crossing of the index fingers should be more pronounced. He also felt that the hand motion was somewhat "jerky" and wondered if the cosmetic covering could be designed such that it would damp or smooth the motion of the hand. Dr. Kruger reiterated his desire that the mechanically formed symbols exactly replicate those made by the human hand.

E. Needed Improvements

These laboratory trials and consultant evaluations to date have helped disclose the need for further improvements or revisions to the mechanical hand system. Some of these observations reflect on the design criteria or the components selected, and others represent evidence that was not available to the designers.

1. Cosmesis

It has been mentioned that a standard, commercially available cosmetic glove was identified early in the project as the solution to the problem of providing realistic appearance and feel for the hand. Application of the glove to the hand, shown in Figure 19, has detrimental effects on the functional performance of the device. Stretching of the glove across the tops of the knuckles and bunching of the material under the joints limit the amount of flexure of fingers and thumb. The resulting characters displayed are not distinct enough for consistent reading. A thorough analysis of the restrictions needs to be performed; but it appears, presently, that building up a rigid contour on the fingers, thumb, and back of palm would permit the use of a thinner, more pliable glove, thus reducing external resistance.

Project resources did not allow cosmetic shaping of the fingers and thumb, nor was it possible to make the contoured appliques needed to cover the pins and hardware protruding from the sides of the fingers.

FIGURE 19. THE MECHANICAL HAND COVERED WITH A COSMETIC GLOVE

This hardware snags the glove and prevents it from freely sliding over the fingers. Carrying out this work should significantly reduce glove-hand interaction.

2. Internal Resistance

Most of the previously discussed functional losses are caused by friction. Although nearly full extension of the fingers and thumb is achieved in the power mode, full flexion is not. In the case of the fingers, this is a serious detriment only to formation of the letter S, where the thumb must flex around the tightly clenched fingers. At present, it is difficult to distinguish between S and A. Full thumb flexion is important to the accurate reproduction of certain characters, especially for the numbers 6 through 9.

The frictional problem in the thumb is due primarily to the complex routing of cables over pulleys of minimum recommended radius. Not only does the friction conflict with thumb flexion, but it also incurs a high static frictional force component affecting spring return.

There also is a frictional loss in the rack gear mechanisms in each finger. Due to the design configuration chosen for cable attachment to the finger, torque is induced in the sliding blocks. This torque is balanced only by the walls of the block guide. For slack cables, the torque couple is small, so the friction is small. However, as cable tension is increased to improve motion response of the fingers, the frictional forces rise. Molybdenum-based lubricants have helped, but have not solved the problem. A final effect of frictional loss is the occasional jamming of the thumb. For certain characters, the fingers close over the thumb. When the fingers fail to relax to their neutral positions, the thumb becomes trapped and is prevented from proceeding to the next symbol.

While friction cannot be totally eliminated, several steps can be taken which should significantly improve the hand. The steps are as follows:

- Refine tolerances of sliding members, particularly in finger mechanisms.
- Use ball bearings on all pulleys. (Only stock pulleys were used and ball bearings were not available in some sizes. Ball bearings can be added to all pulleys at minimal cost.)
- Respecify cable.
- Reroute thumb cables.

3. Smoothness of Operation

Because the pull of the driver solenoid is only frictionally damped, movement of the mechanical hand is not as smooth as that of a human hand. The abrupt movements of the wrist and forearm are especially noticeable, since they are powerful enough to displace the hand of the reader. Program consultants indicate that they could adjust to the abrupt movements, but would prefer a more "fluid" transition from one letter to another. There appears to be a relationship between speed of communication (rate of change of signs) and the effect of the quick movements, but the exact relationship has not been characterized. Smoother movements may result in faster communication rates. It is felt that the addition of a suitable cosmetic glove will significantly smooth the hand's motion. Elastomeric materials have viscous properties which have a damping effect. It is expected that a lubricant will be needed between the glove and the hand to provide free movement, and this will also provide some viscous damping.

4. Adjustment Capability

It has been suggested that each user may require a different rate of presentation and a corresponding change in the time for holding each character. Currently, holding time can be adjusted over a fixed range, but this adjustment is located inside the electronics cabinet. Adaptability of different people with varying reading skills would be enhanced if the rate were controlled by a dial conveniently located on the panel. A capability for adjusting location and attitude of the hand would also be valuable features. Varying the height and vertical angle would help to adapt to different reading styles.

Other mechanisms for adjustment should be considered. Convenient means for "tuning" finger position, range of motion, pulling force, cable tension, spring tension, and displacement angles would also be desirable.

5. Portability

Design criteria for the device included portability. The existing system, however, is neither compact nor lightweight. The solenoid drive method, while providing a flexible system for design evaluation, is large and heavy. The solenoids themselves are heavy and their power requirement dictates a large, heavy power supply. While the weight and bulk should not be reduced at this time, a useful improvement would be to package the system in a roll-around cabinet or cart.

6. Special Functions

Experience in operating the device and observation of deaf/blind persons has made it clear that some special functions in addition to the alphanumeric characters are needed. When a word requires a double letter,

there is no provision for repeating except to wait for the first execution to relax before activating the same letter. Certain common conversational words such as "the", "and", "yes", and "no" have acceptable one-hand symbols which are within the capabilities of the mechanical hand, but they have not been programmed and are consequently not available. Keys are available on the keyboard to control these symbols.

V. CONCLUSIONS

A fully-articulated mechanical hand has been designed and fabricated. The device has life-like appearance and performance even though it does not yet have a suitable cosmetic covering. It will form acceptable symbols for much of the one-hand manual alphabet at a speed approaching a conversational rate. The corrections needed to better define the remaining letters are matters of minor modification and refinement of discrete components and reprogramming. The reprogramming, particularly, must be performed in collaboration with deaf-blind consultants. It is felt that the mechanical hand still retains promise as a communication aid and as a teaching tool for deaf-blind people.

VI. RECOMMENDATIONS

The design of the mechanical hand communicator has proved to be functional. However, as with any new design, a number of deficiencies and problems (bugs) have been found which must be corrected before optimum operation is obtained. In addition, cosmetic features of the hand demand attention and effort as determined in the design study. Systematic follow-on development of the hand should continue as follows.

A. Functional Design Evaluation

A short but intensive period should be devoted to demonstration of the hand to a selected group of deaf-blind users. Comments, criticisms (all functional) and recommendations should be solicited regarding characteristics of the system. Particular attention should be given to range of motion, hand attitude, optimal "rest" position, symbol formation, and transition motions. Where possible, these sessions should include "on-the-spot" changes through mechanical adjustment and reprogramming. This will allow the designers and consultants to immediately evaluate suggestions and to rapidly arrive at suitable modifications or compromises.

B. Engineering Analysis and "Debugging"

This effort should be performed concurrently with the Functional/Design Evaluation. The results of the functional evaluation should be utilized to measure, analyze, and develop corrective measures. Needed refinements of parts and reduction of internal friction should be identified. Some components of the hand, particularly in the finger actuator mechanism, should be redesigned or modified. A search for alternate stock components, especially ball bearing pulleys and cables, should be made. Depending upon time and resources available, packaging of the system should be redesigned to facilitate hand positioning and transport of the system.

C. Modification

Alterations and changes identified in Section V. A. and V. B. should be made. An instruction and service manual and a stock of essential spare parts should be provided. The spare parts should include primarily moving parts, cables, and cable terminators; spare hardware (screws, fasteners, etc.) and lubricants should be included. The manuals and spare parts inventory would be essential if the hand is sent to other institutions for evaluation. If funds allow, the system should be repackaged to provide easier transportability and hand attitude adjustment.

D. Cosmetology

This phase should be devoted to shaping of the fingers, shaping of contoured appliques, and fabrication of the glove. The fingers need to

be tapered in their vertical dimension. The appliques should initially be made of balsa wood, inletted and glued to the sides of the fingers and shaped by carving and sanding. The pieces should be removed and used to form casting molds. Plastic replicas should be molded and glued to the fingers to cover the protruding hardware and to provide shape to the fingers. Additional appliques will probably be required for the palm and forearm. The cosmetic glove should be specially made to fit the contoured hand. Gussets should be designed into the glove in the region of the joints. Design and fabrication of the glove should undoubtedly be done by a company specializing in cosmetic coverings for protheses.

E. Concept Evaluation

Upon completion of the improvements discussed above, the device should be sent to the field for an extensive, non-biased evaluation by potential users. This field evaluation should be tightly structured and performed under a trained educator or educational psychologist. The study should include formal training of the users, formal exercises for proficiency development and, finally, a period of practical use as an interpersonal communicator and/or as a text reader ("talking" or "signing" book). Throughout this program, quantitative proficiency evaluations of the users should be made. The data can be used for both developing learning parameters and identifying additional improvements which should be made in the device. When a population of skilled users has been developed, additional design studies can be pursued such as optimization of hand strength, speed, hand inclination, etc.

F. Final Disposition

Upon completion of the users' evaluations, a comprehensive final report should be prepared. This should include adequate drawings, and parts list and specifications. If warranted, a manufacturer should be identified.

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